Heavy quark transport: from heavy flavor hadrons to heavy flavor jets

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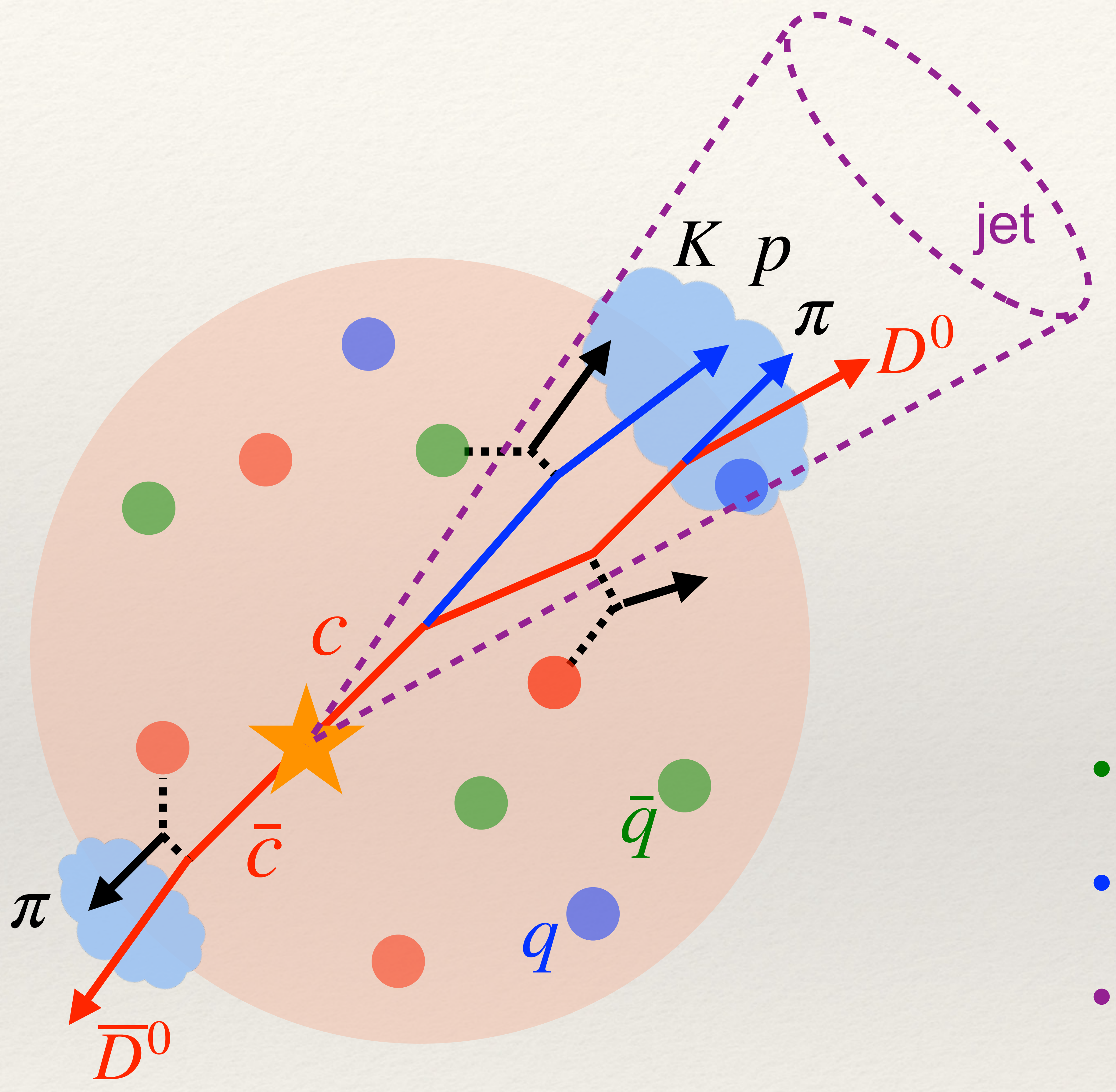
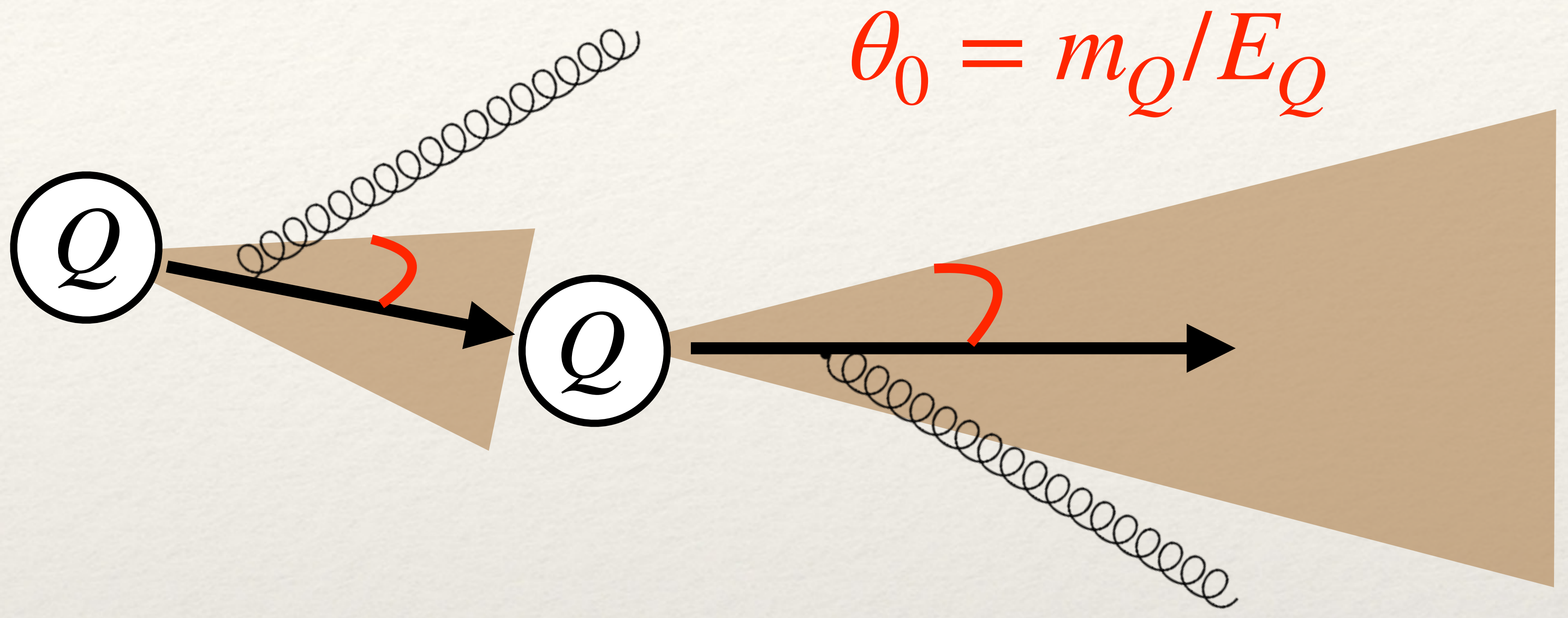
SoftJet 2024, Tokyo

Heavy quarks in high-energy nuclear collisions

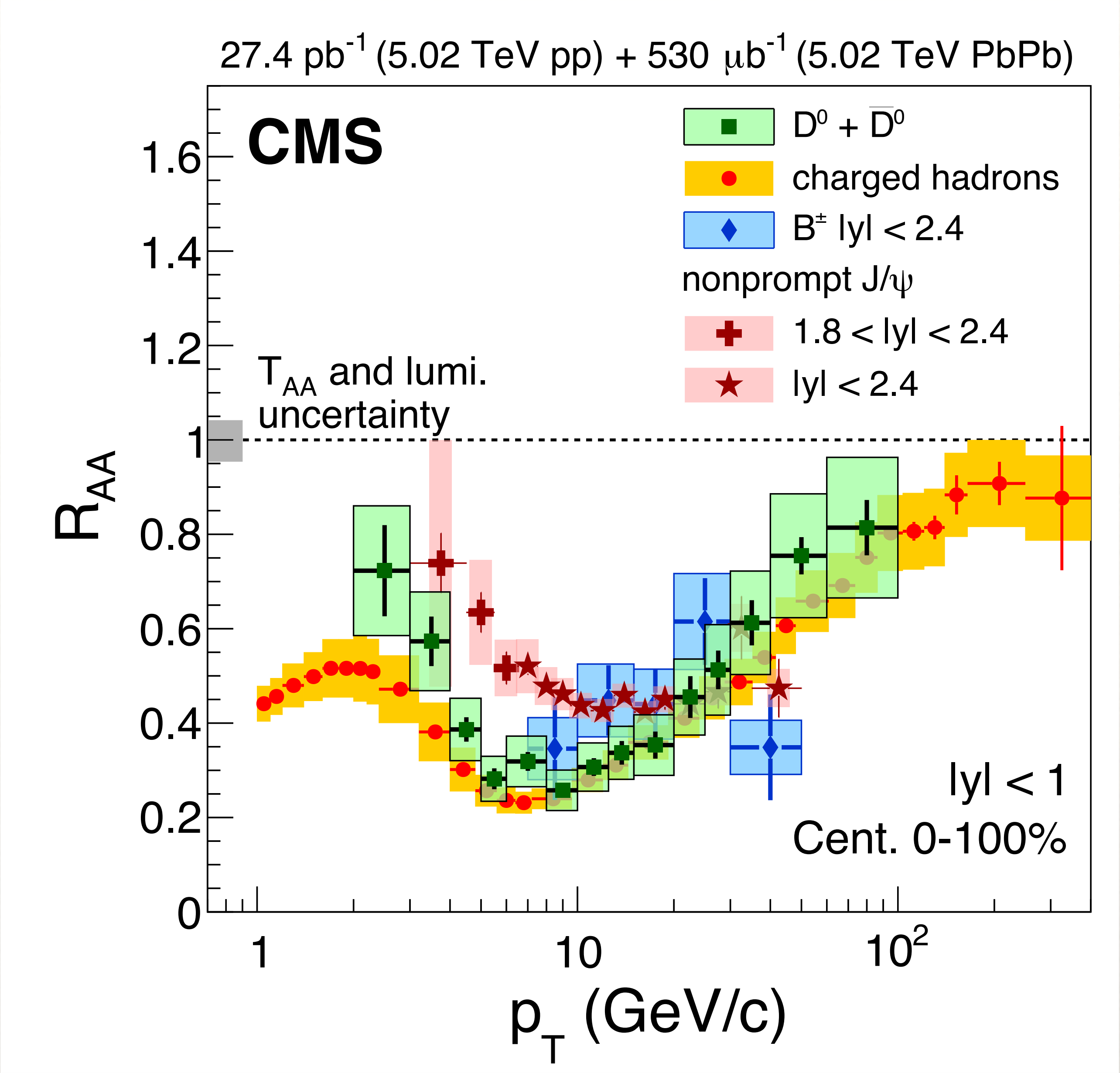




- Produced from initial hard scatterings
- Serve as an ideal probe of the QGP properties
- Provide a unique opportunity for studying the flavor dependence of parton splitting (dead cone effect)

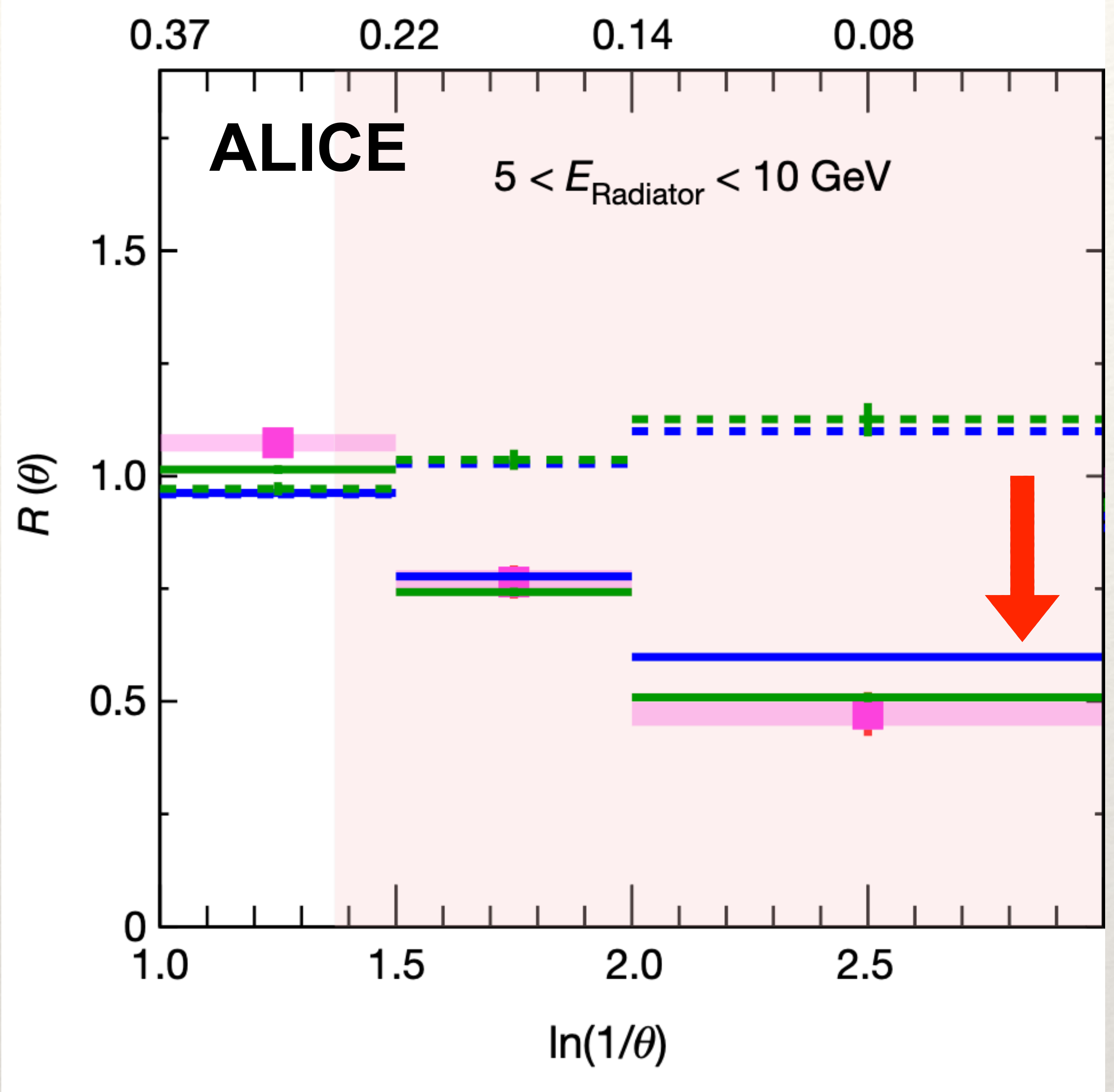
Searches for the flavor dependence of parton splitting

Hadron R_{AA} (parton energy loss)



Phys. Lett. B 782 (2018) 474-496

Distribution of splitting angles in *pp*



Nature 605 (2022) 7910

No clear separation between charged hadrons, *D*, and *B*, except at very low p_T

Clear suppression of splitting at small θ in *D*-jets *vs*. inclusive jets

Goals:

- Understand flavor hierarchies embedded in both hadrons and jets
- Use heavy flavor observables to probe the QGP properties

Transport model for parton-QGP interactions

Linear Boltzmann Transport (LBT)

$$p_a \cdot \partial f_a(x_a, p_a) = E_a(\mathscr{C}_a^{\mathrm{el}} + \mathscr{C}_a^{\mathrm{inel}})$$

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Elastic energy loss ($ab \to cd$)

$$\mathcal{C}_a^{\text{el}} = \sum_{b,c,d} \int \prod_{i=b,c,d} \frac{d[p_i]}{2E_a} (\gamma_d f_c f_d - \gamma_b f_a f_b) \cdot (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) \left| \mathcal{M}_{ab \to cd} \right|^2$$

$2 \to 2$ scattering matrices

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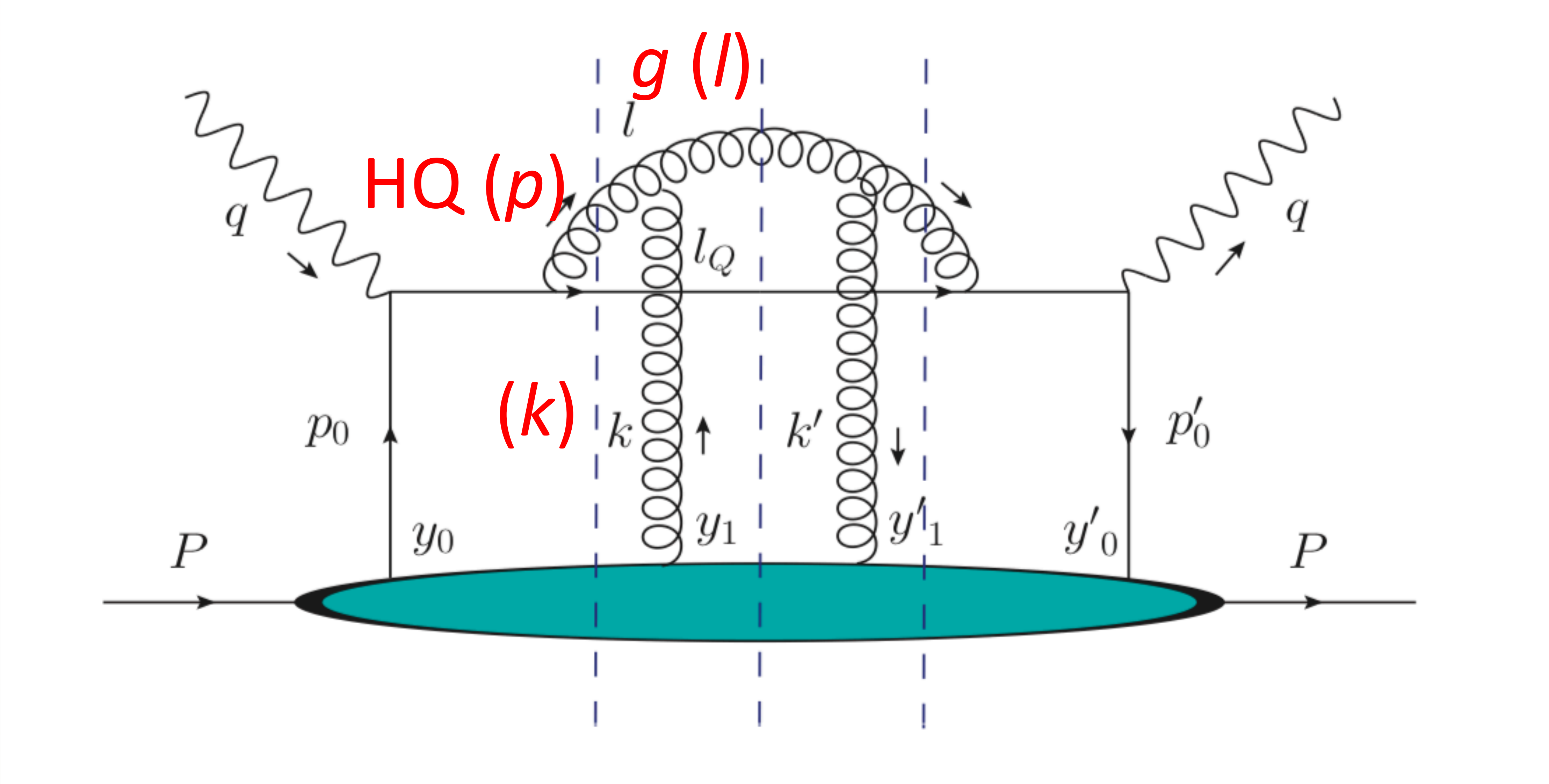
$2 \to 2$ scattering matrices

loss term: **scattering rate**
(for Monte-Carlo simulation)

$$\Gamma_a^{\text{el}}(\mathbf{p}_a, T) = \sum_{b,c,d} \frac{\gamma_b}{2E_a} \int \prod_{i=b,c,d} d[p_i] f_b \cdot (2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d) |\mathscr{M}_{ab\to cd}|^2$$

Inelastic energy loss



Majumder PRD 85 (2012); Zhang, Wang and Wang, PRL 93 (2004)

- **Higher-twist formalism**: collinear expansion ($\langle k_\perp^2 \rangle \ll l_\perp^2 \ll Q^2$)

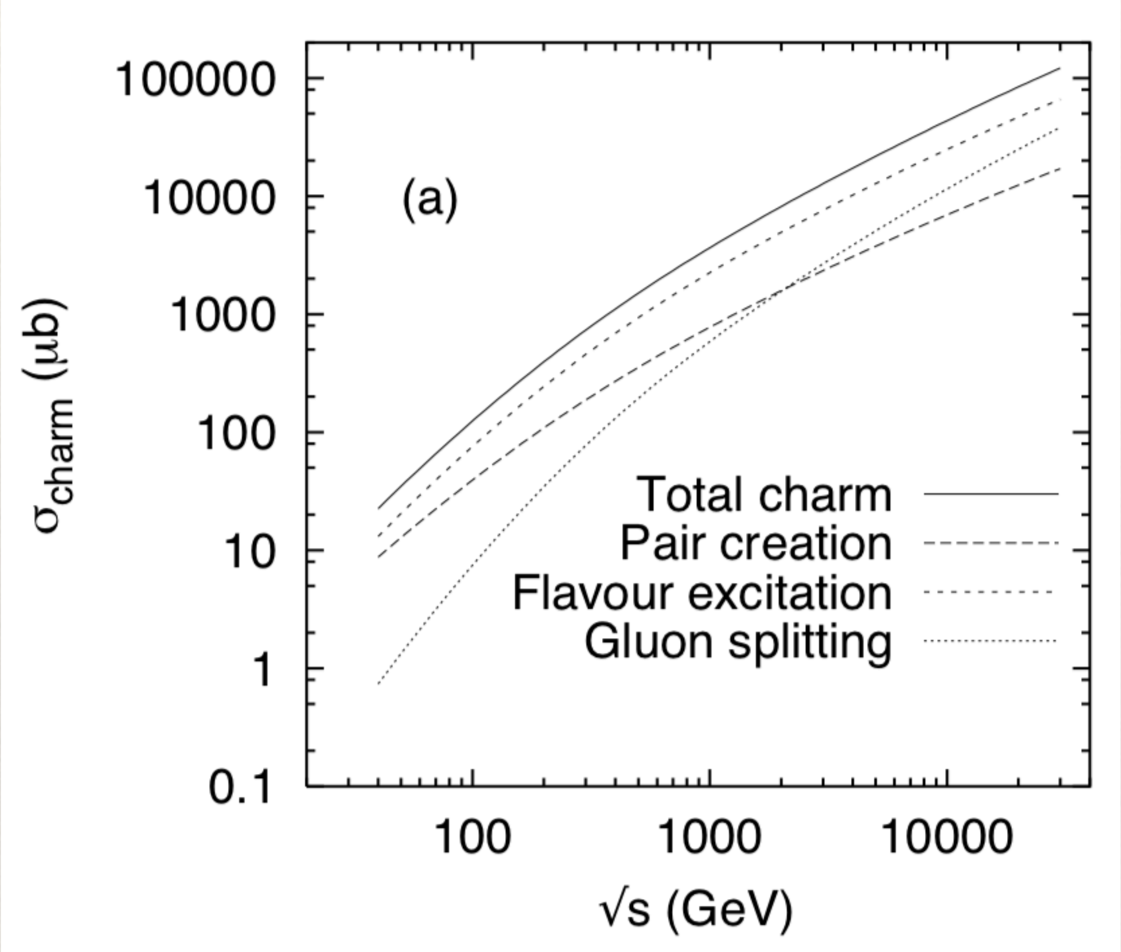
$$\frac{d\Gamma_a^{\rm inel}}{dz dl_\perp^2} = \frac{dN_g}{dz dl_\perp^2 dt} = \frac{6\alpha_s P(z) l_\perp^4 \hat{q}}{\pi(l_\perp^2 + z^2M^2)^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

- Medium information absorbed in $\hat{q} \equiv d\langle p_\perp^2 \rangle / dt$

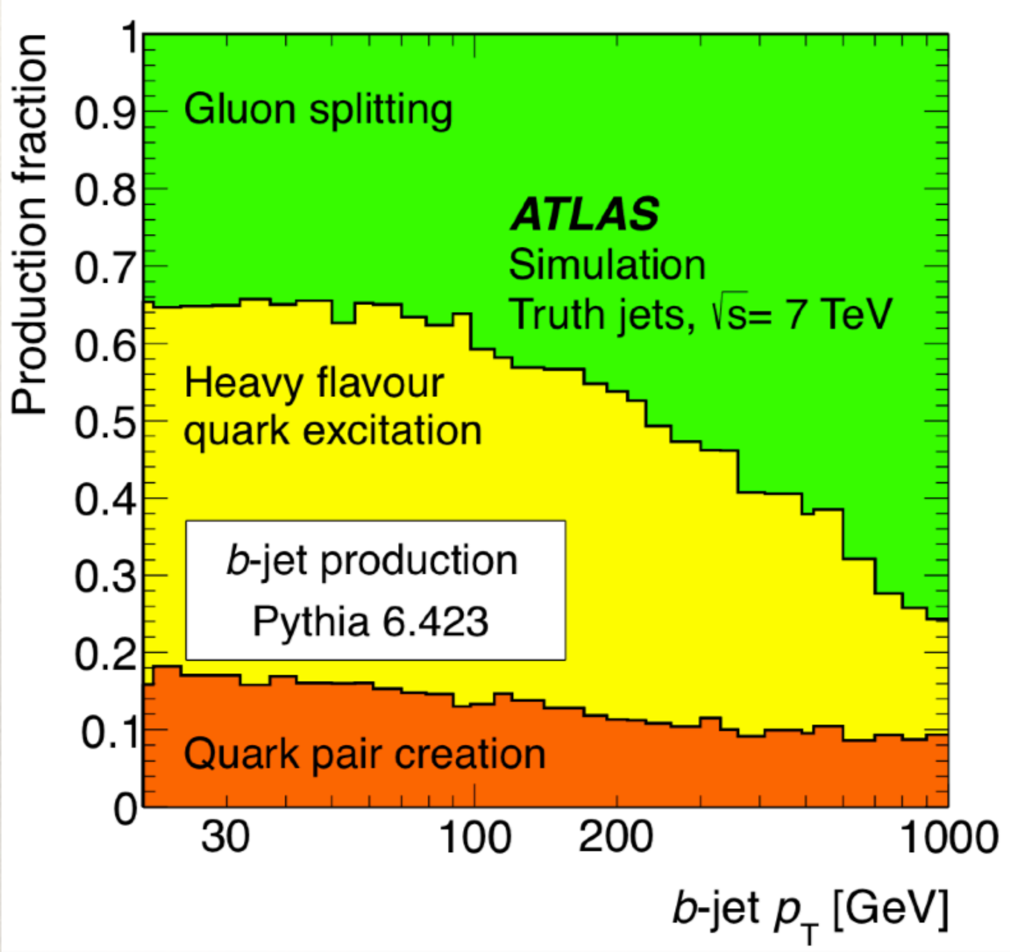
Flavor hierarchy in hadron suppression

- Hadron production in *pp* collisions: NLO production + fragmentation

NLO contribution to HQ production in Pythia simulation (gluon splitting)



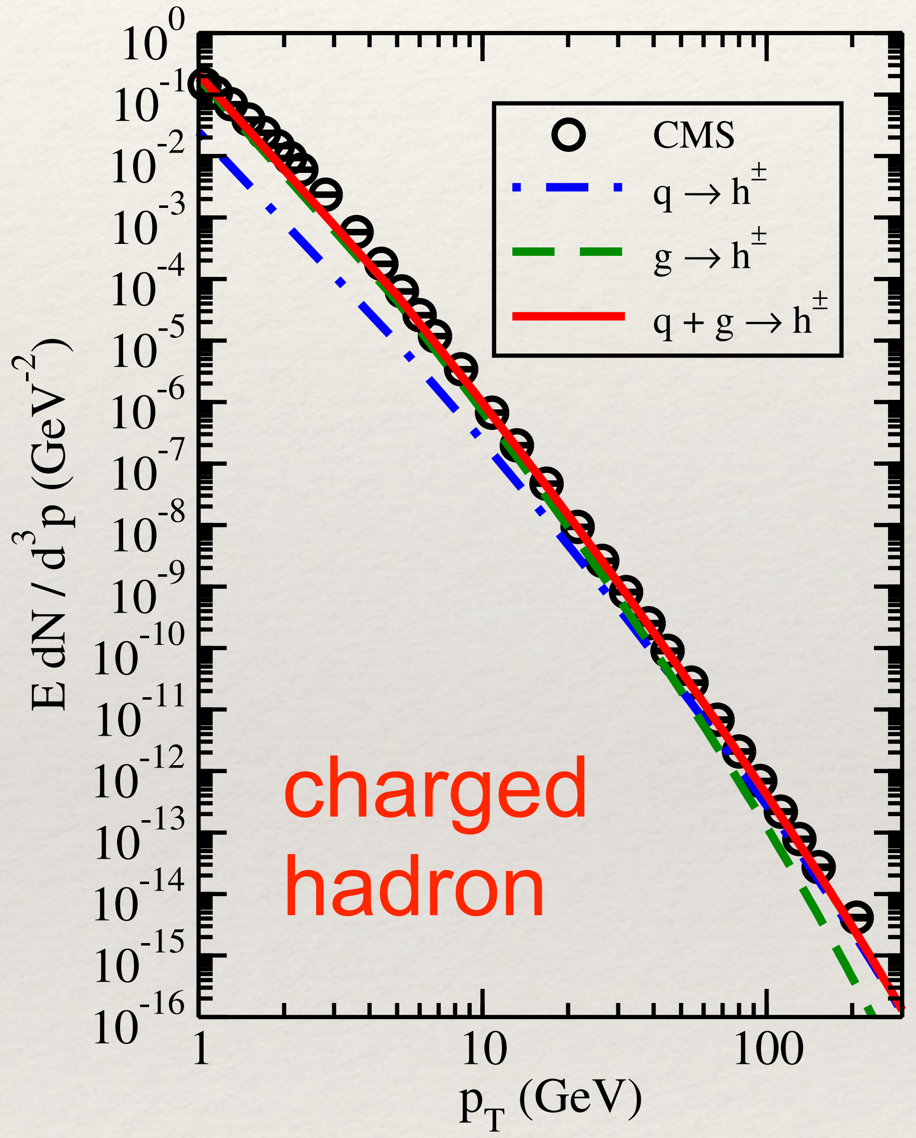
[Norrbin and Sjostrand, EPJC 17 (2000)]

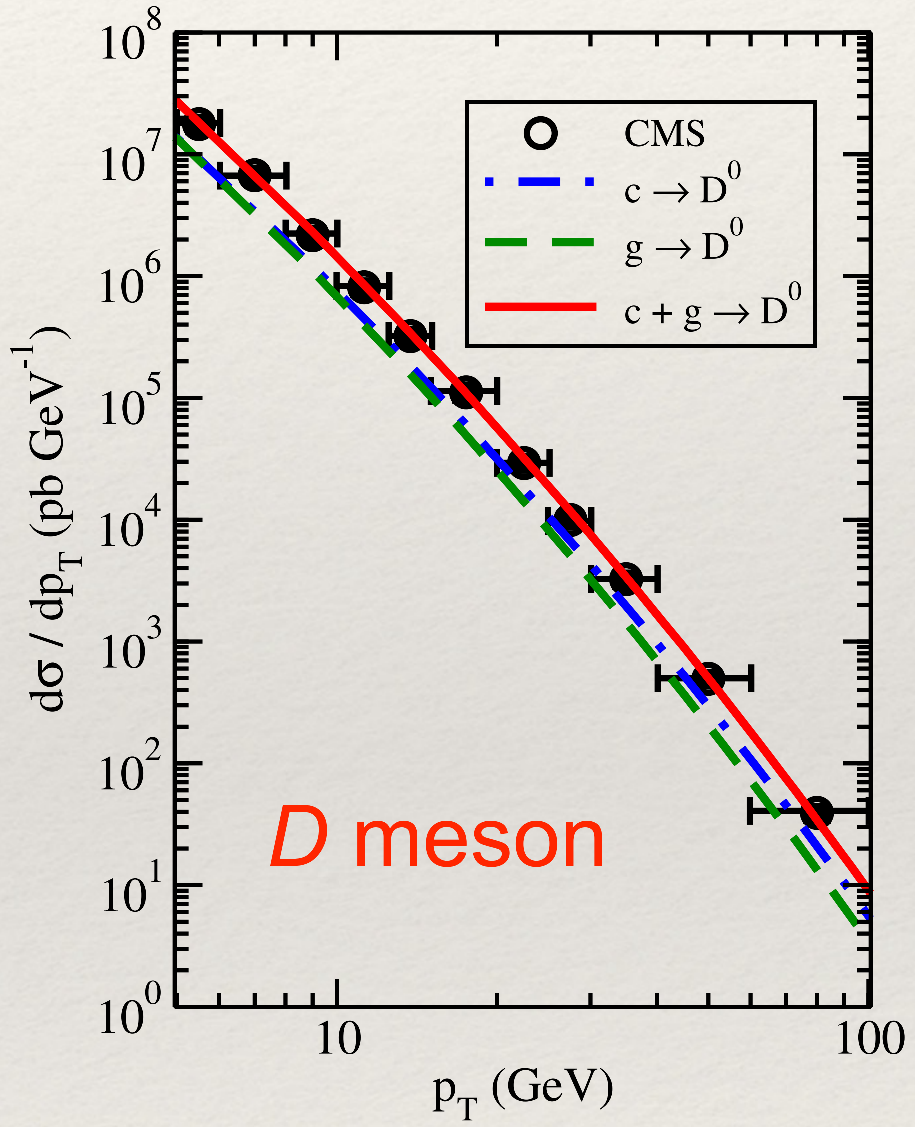


[ATLAS, EPJC 73 (2013)]

- NLO contribution increases with $\sqrt{s}$
- NLO contribution increases with *b*-jet p_T

Different NLO contributions to light and heavy flavor hadrons



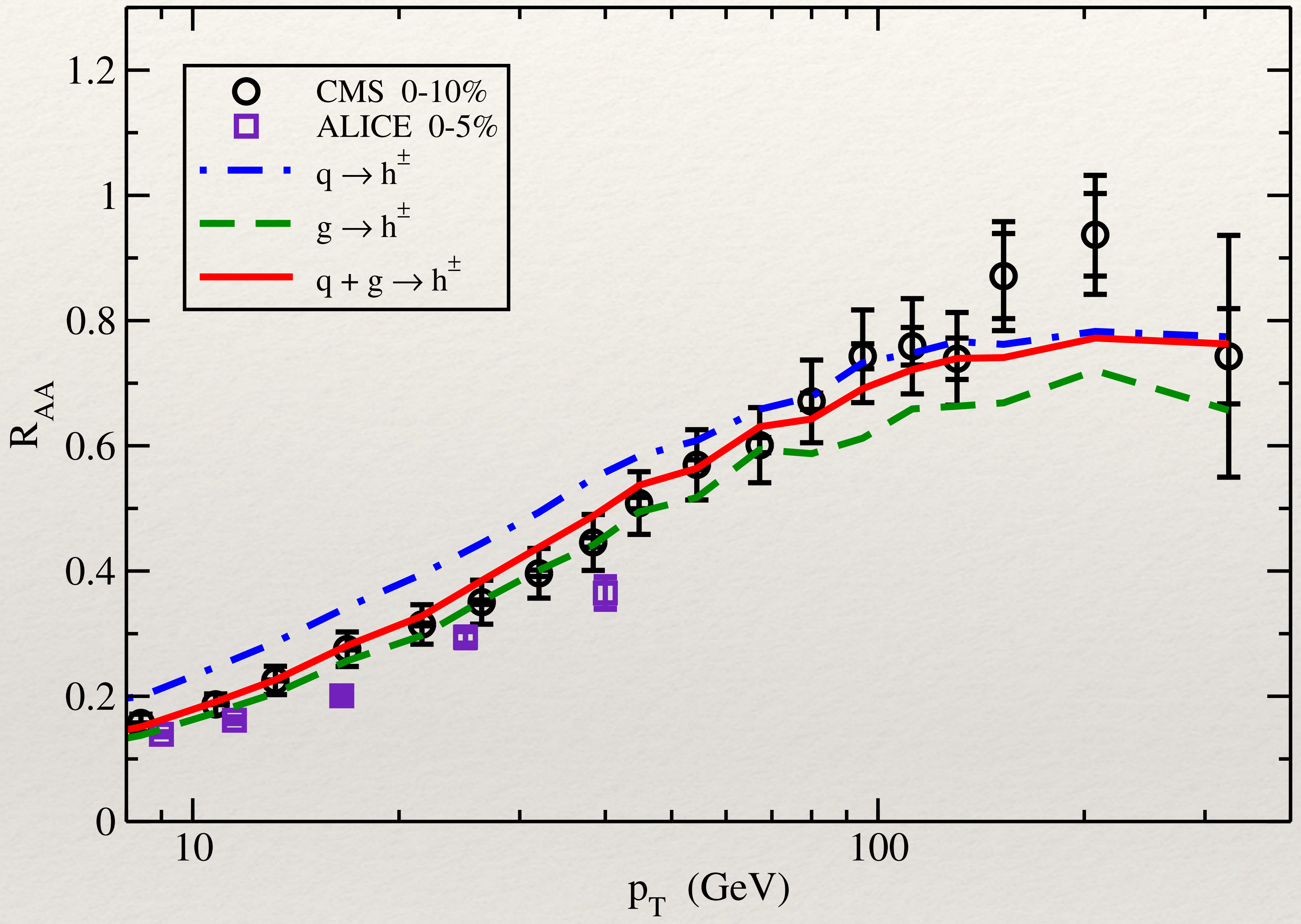


- dominates $h^{\pm}$ production up to 50 GeV
- contributes to over 40% *D* up to 100 GeV

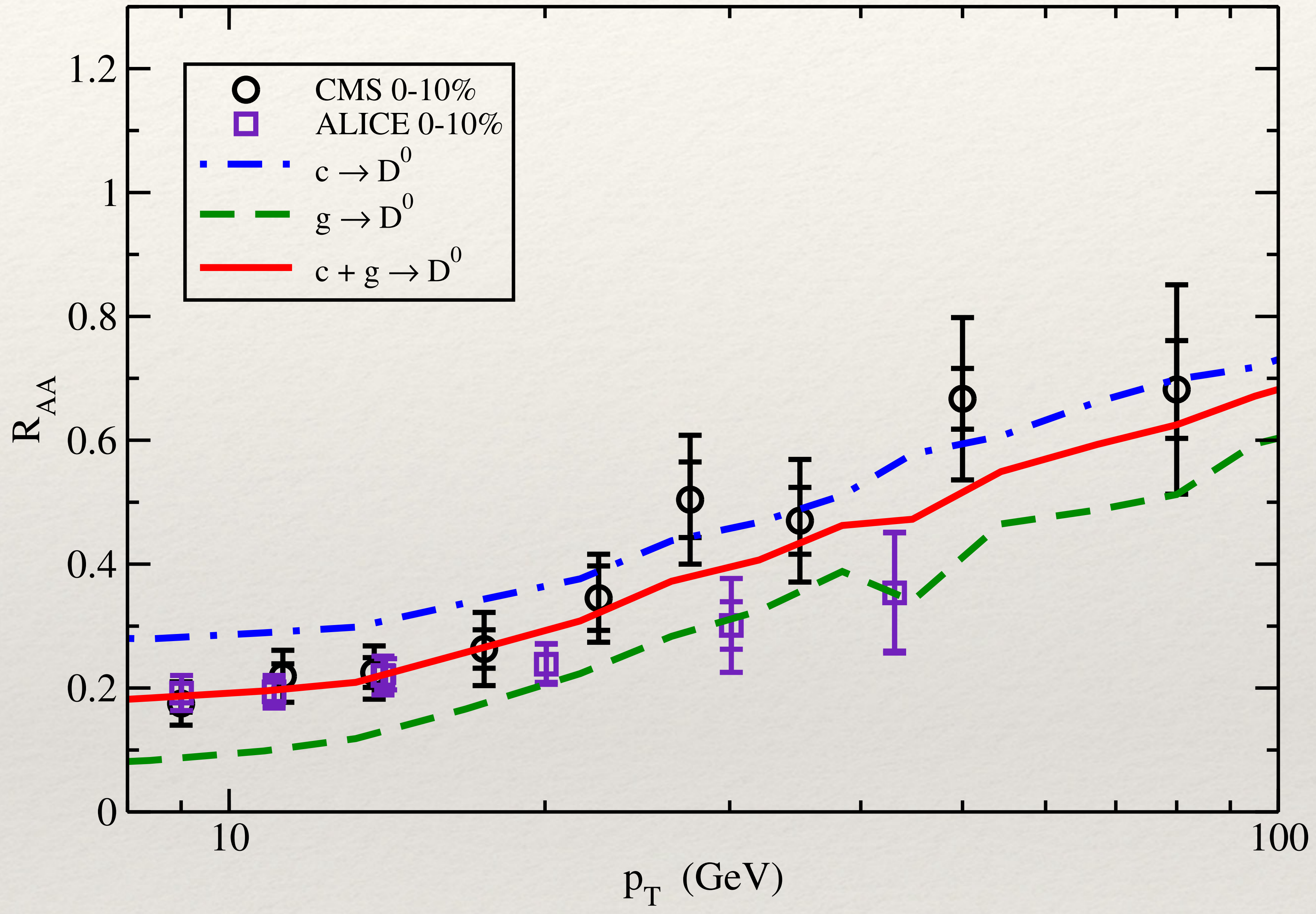
Flavor hierarchy in hadron suppression

NLO initial production and fragmentation + Boltzmann transport + hydrodynamic medium for QGP

charged hadron



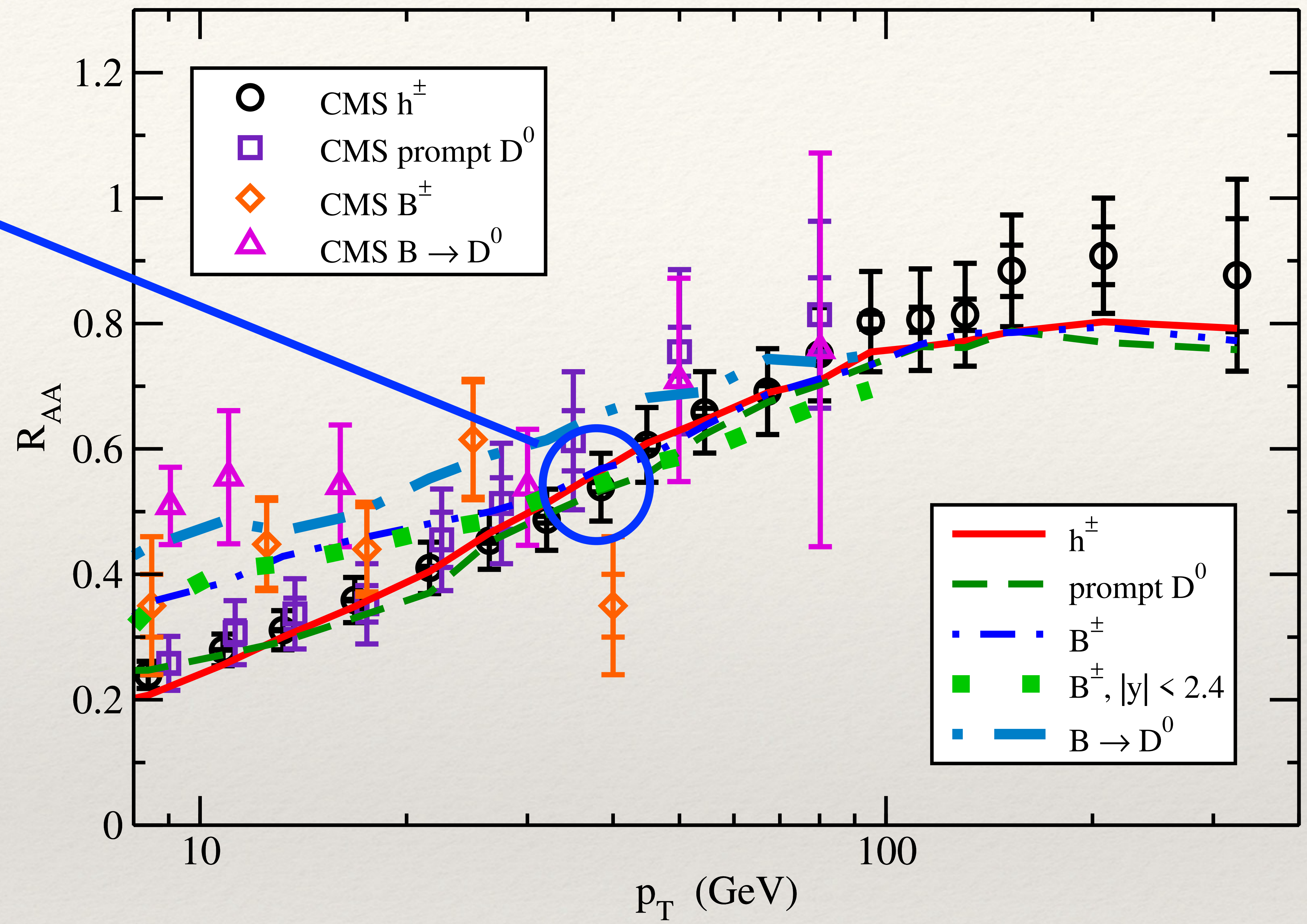
D meson



- *g*-initiated *h* & *D* R_{AA} < *q*-initiated *h* & *D* R_{AA} [$\Delta E_g > \Delta E_{q/c}$]
- R_{AA} (*c*->*D*) > R_{AA} (*q*->*h*) [$\Delta E_q > \Delta E_c$], R_{AA} (*g*->*D*) < R_{AA} (*g*->*h*) [different FFs] => R_{AA} (*h*) ≈ R_{AA} (*D*)
- Signature of flavor hierarchy of parton ΔE offset by NLO production/fragmentation in hadron R_{AA}

Flavor hierarchy in hadron suppression

Merging of *D* and *B* R_{AA} at p_T ~ 40 GeV



Xing, SC, Qin and Xing, Phys. Lett. B 805 (2020) 135424

- A simultaneous description of charged hadron, *D* meson, *B* meson, *B*-decay *D* meson R_{AA}'s starting from p_T ~ 8 GeV
- Predict R_{AA} separation between *B* and *h* / *D* below 40 GeV, but similar values above – **wait for confirmation from future precision measurement**

Extraction of parton energy loss from hadron R_{AA}

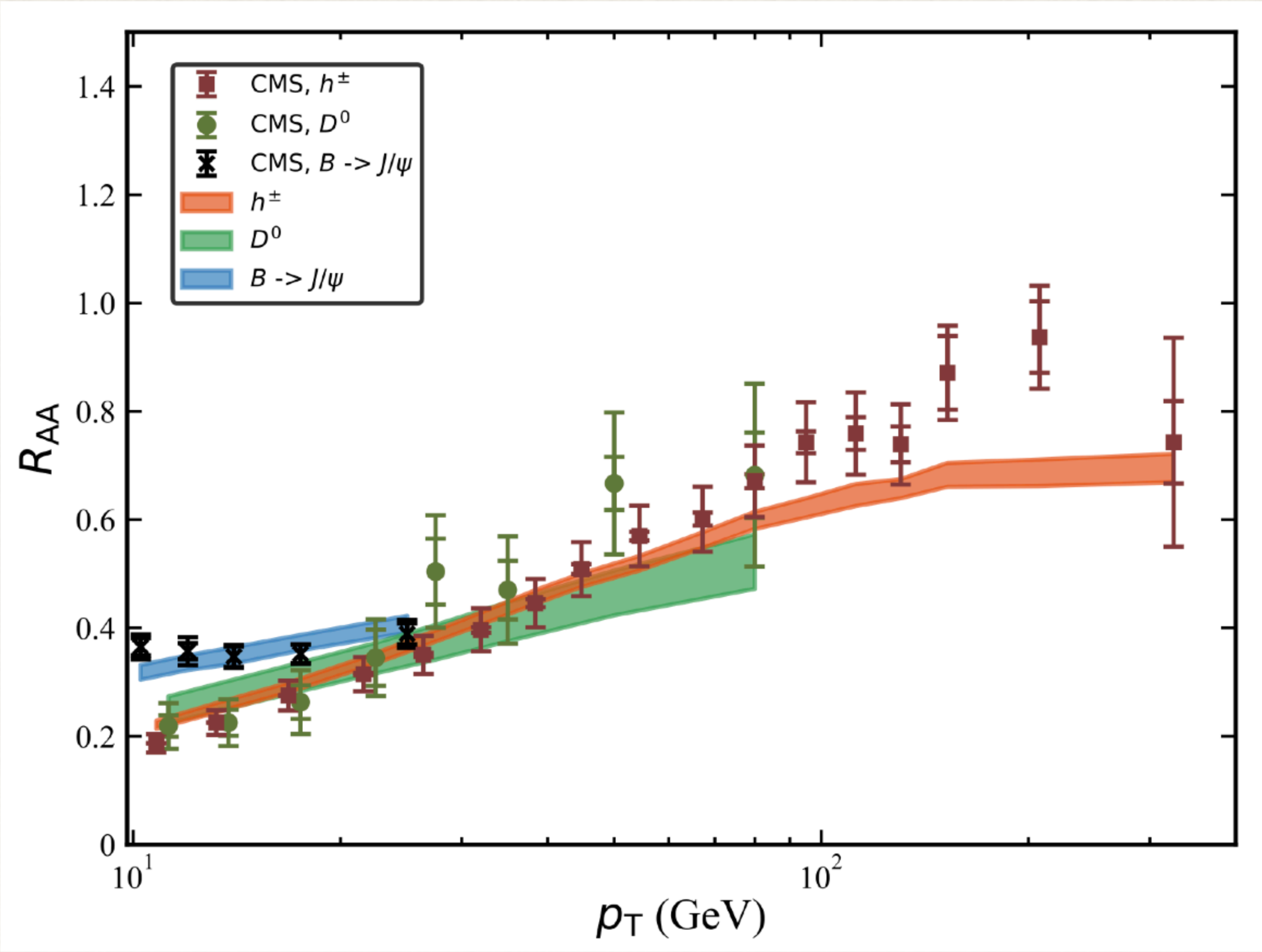
NLO initial production and fragmentation + **Parametrized** parton energy loss inside the QGP

[Xing, SC, Qin, Phys. Lett. B 850 (2024) 138523]

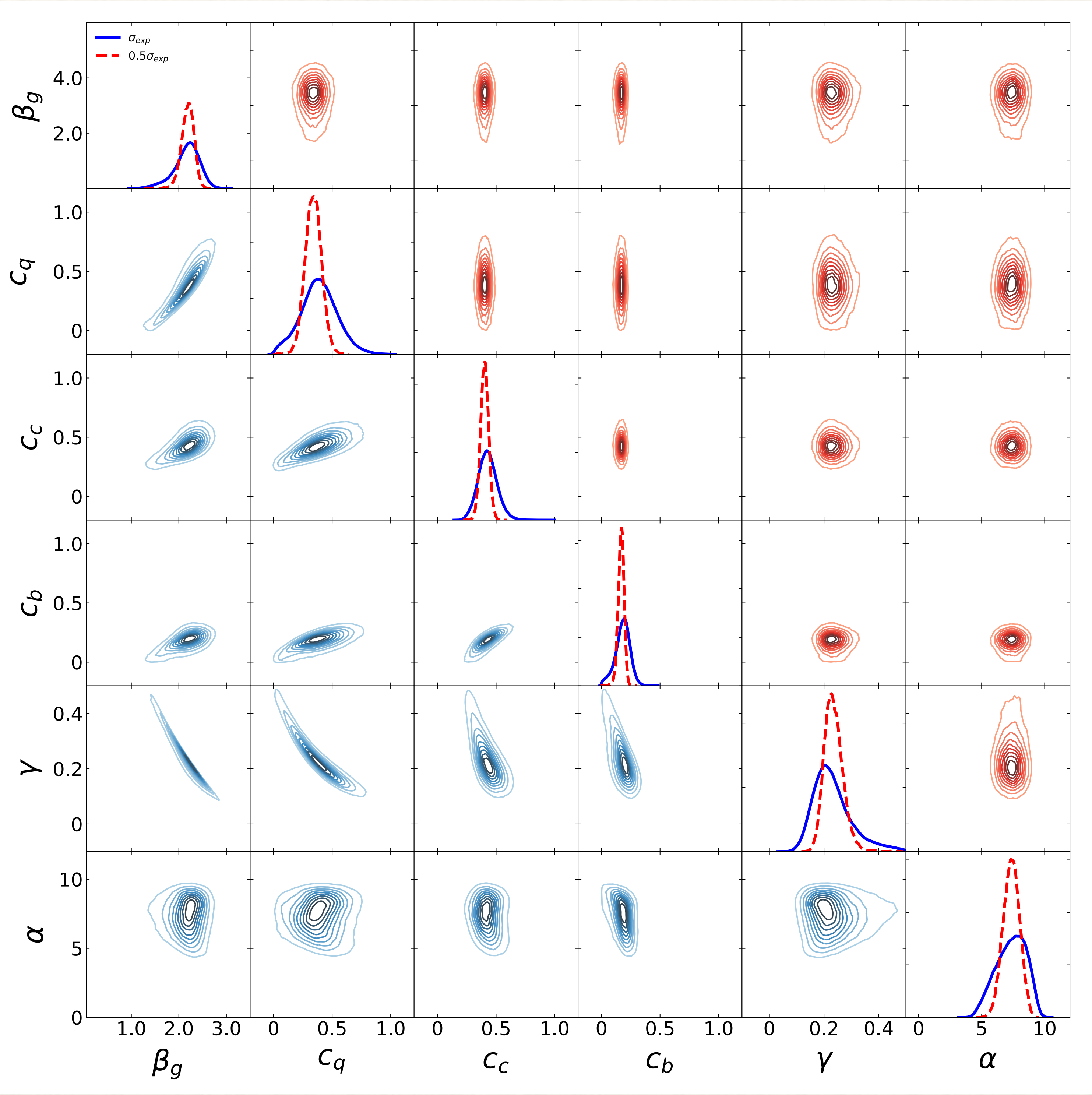
- Mean p_T loss: $\langle \Delta p_T^j \rangle = C_j \beta_g p_T^\gamma \log(p_T)$
  - β_g: overall magnitude for *g*
  - C_j: flavor dependence
  - γ: p_T dependence
- p_T loss distribution:

$$W_{AA}(x) = \frac{\alpha^\alpha x^{\alpha-1} e^{-\alpha x}}{\Gamma(\alpha)}$$

$$x \equiv \Delta p_T / \langle \Delta p_T \rangle$$



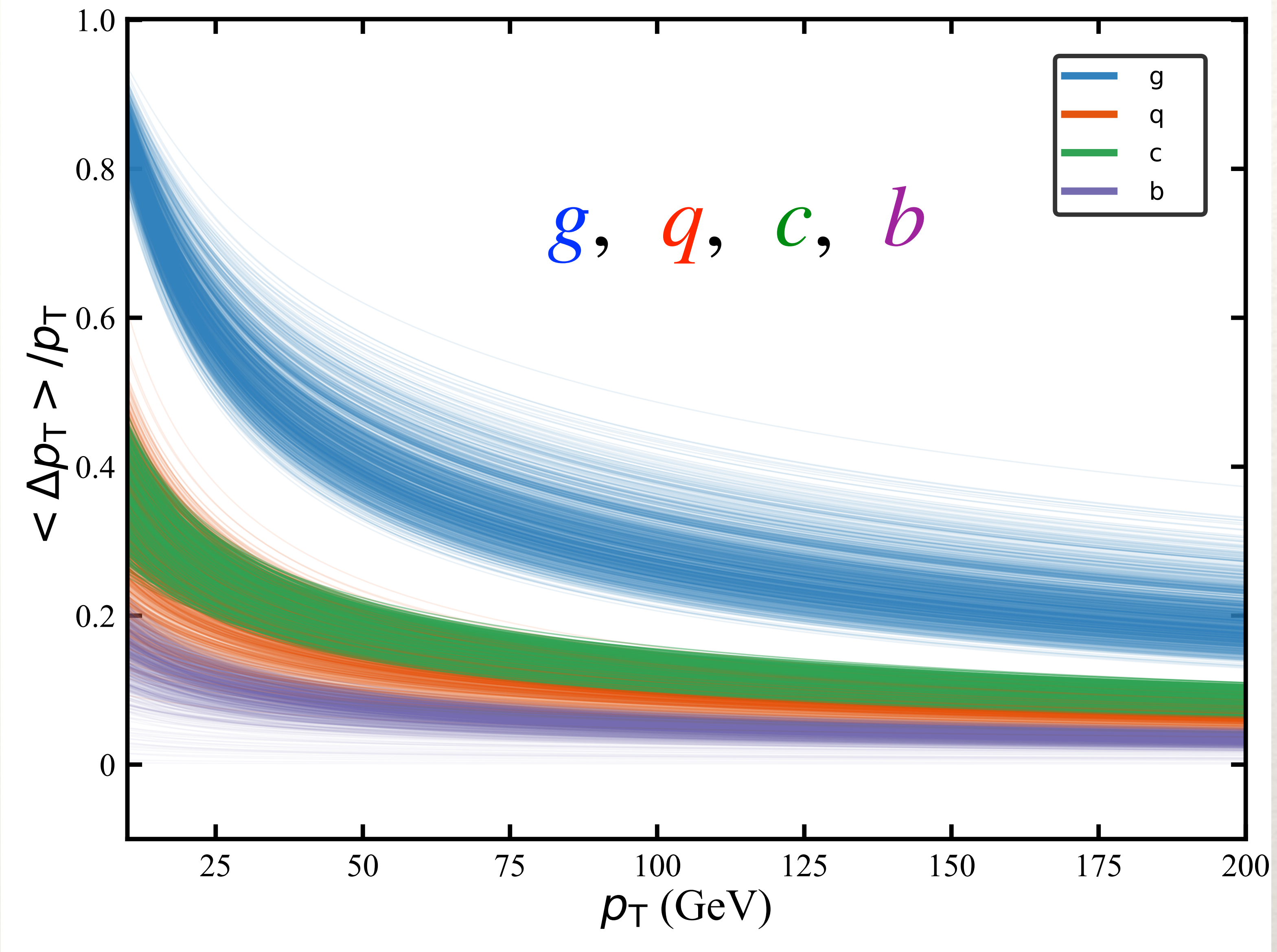
Bayesian calibration to data



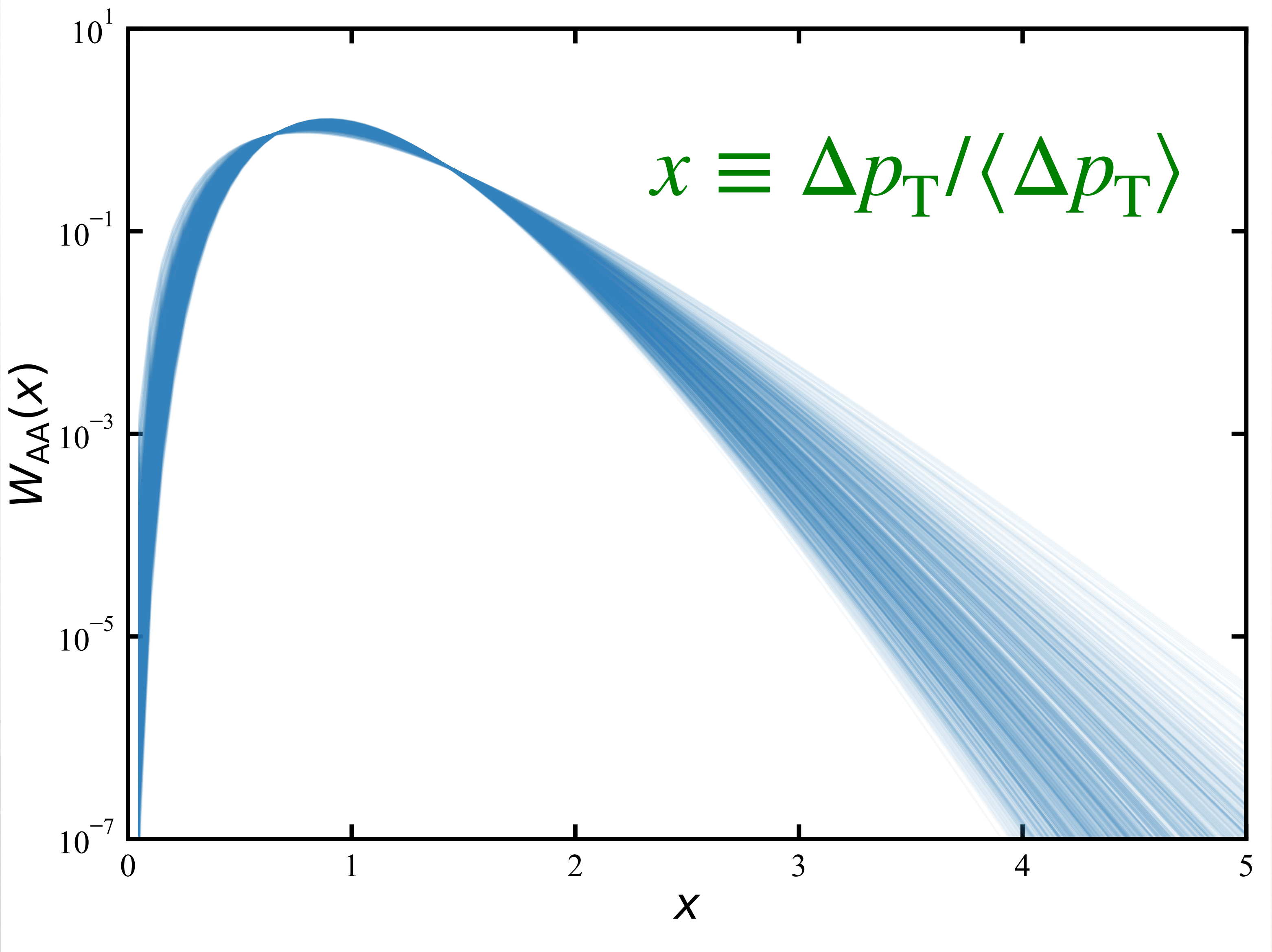
Constraints on parameters

Extraction of parton energy loss from hadron R_{AA}

Average energy loss



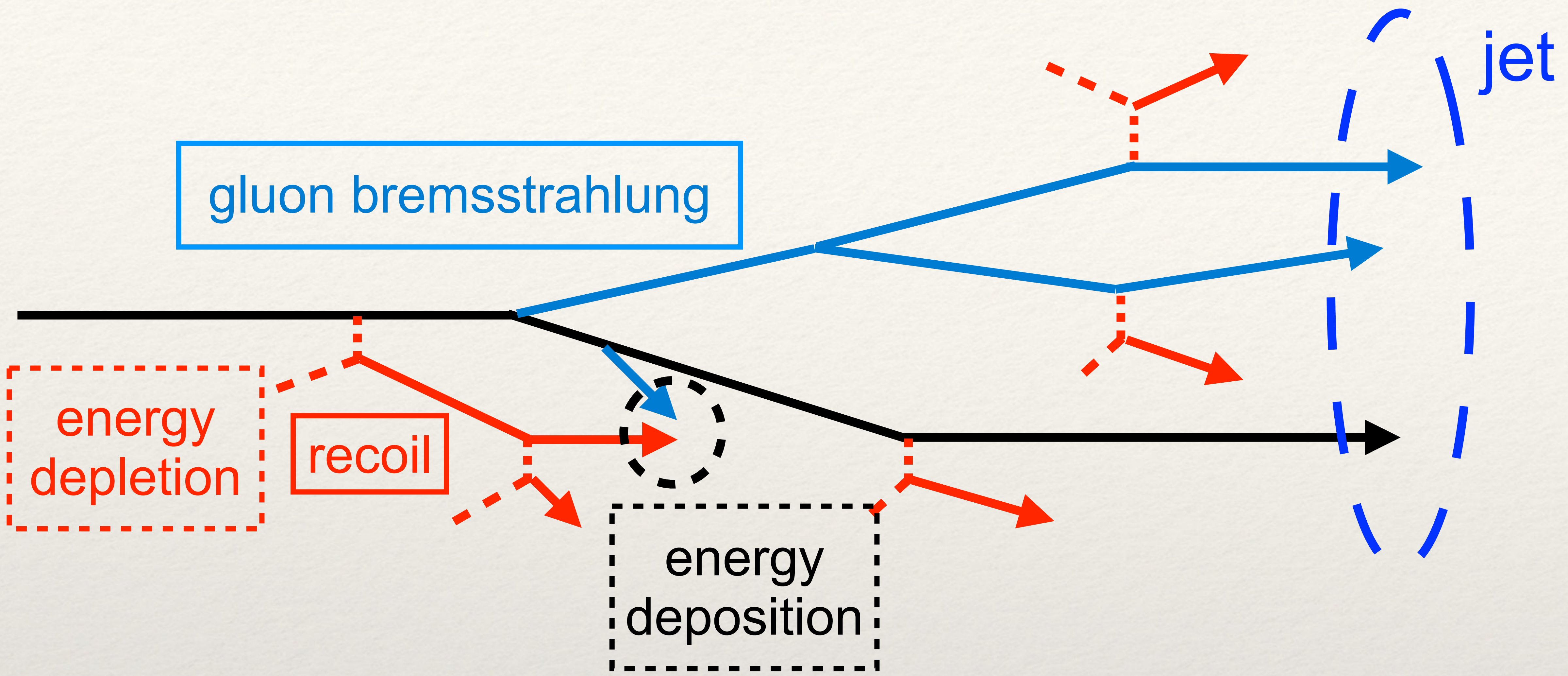
Energy loss distribution

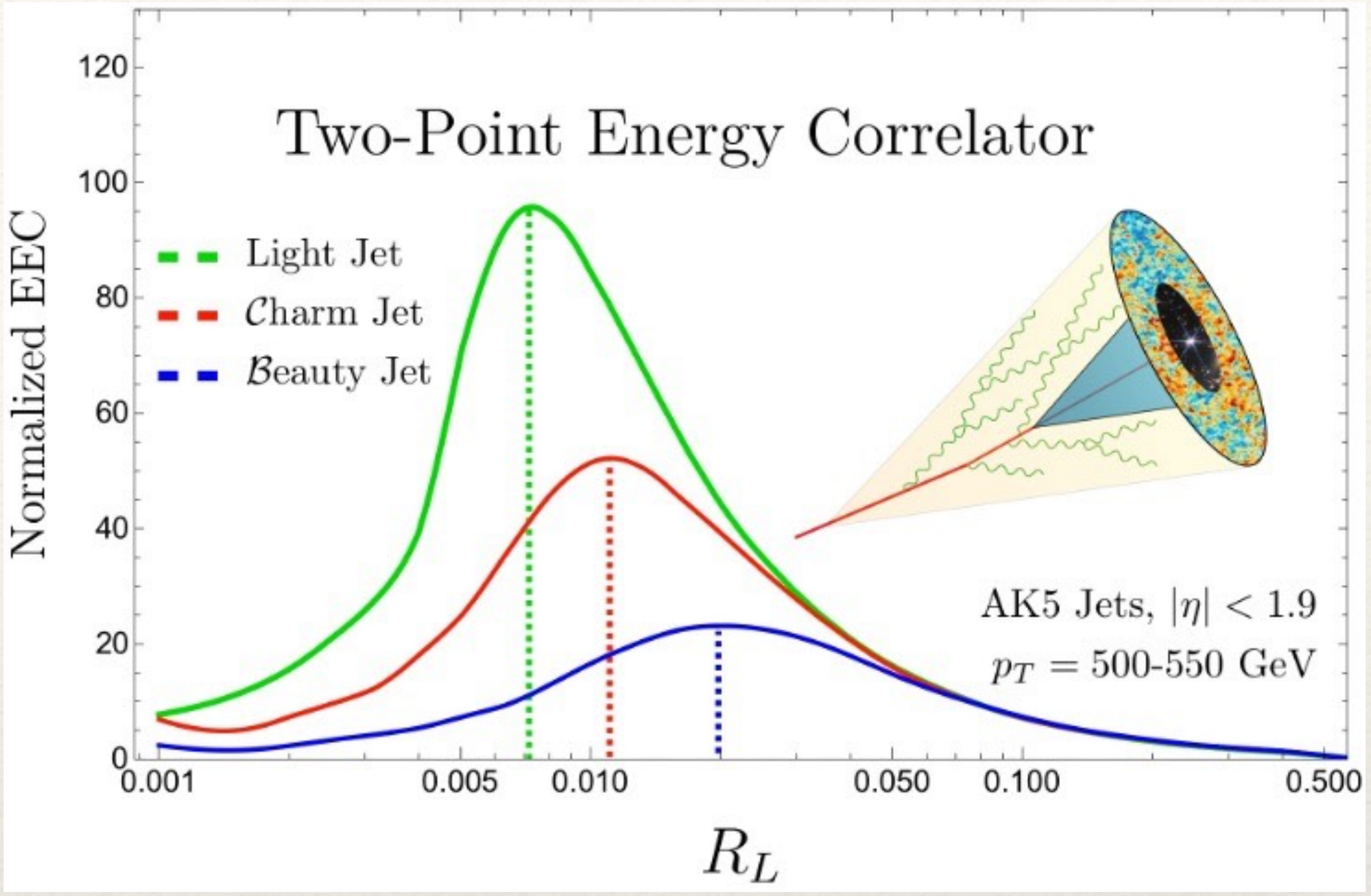


- $\Delta E_g > \Delta E_q \sim \Delta E_c > \Delta E_b$
- More stringent test on QCD calculation

- Flavor hierarchy of parton energy loss is encoded in the hadron R_{AA} data
- No obvious hierarchy for the hadron R_{AA} itself, due to the interplay between energy loss and NLO production and fragmentation

From heavy flavor hadrons to heavy flavor jets

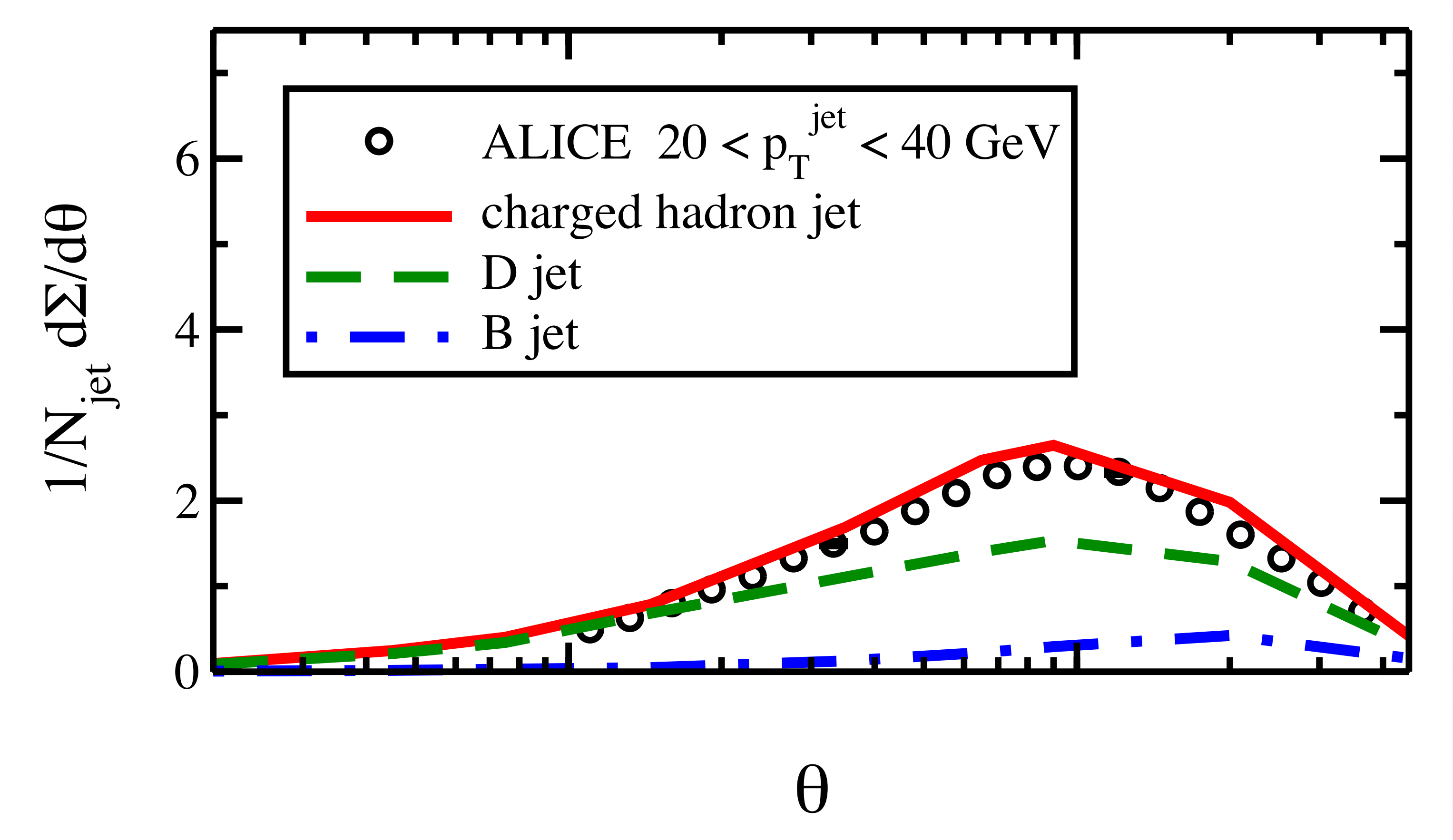




[Craft et. al., arXiv:2210.09311]

- Description of full jets requires both medium modification on jets and jet-induced medium excitation (recoil + energy depletion)
- Energy-energy correlator (EEC) of jets presents a clear angular scale separation between perturbative and non-perturbative (e.g. hadronization) regions
- EEC can also reveal the flavor dependence of splitting angles of partons in *pp* collisions
- Implement a first realistic calculation on light and heavy flavor jet EEC in AA collisions

Light *vs.* heavy flavor jet EEC in *pp* collisions



- Jet in *pp*: Pythia 8 simulation
- EEC of a jet (constituents denoted by *i*, *j*)

$$\frac{d\Sigma(\theta)}{d\theta} = \frac{1}{\Delta\theta} \sum_{|\theta_{ij}-\theta|<\theta/2} \frac{p_{\mathrm{T},i}(\vec{n}_i)\, p_{\mathrm{T},j}(\vec{n}_j)}{p_{\mathrm{T,jet}}^2}$$

- Flavor (mass) dependence:
  - Overall magnitude: charged jet > *D*-jet > *B*-jet
  - Typical (peak) angle: charged jet < *D*-jet < *B*-jet

  Suppression of splitting within $\theta_0 \sim m_Q/E_Q$ in vacuum

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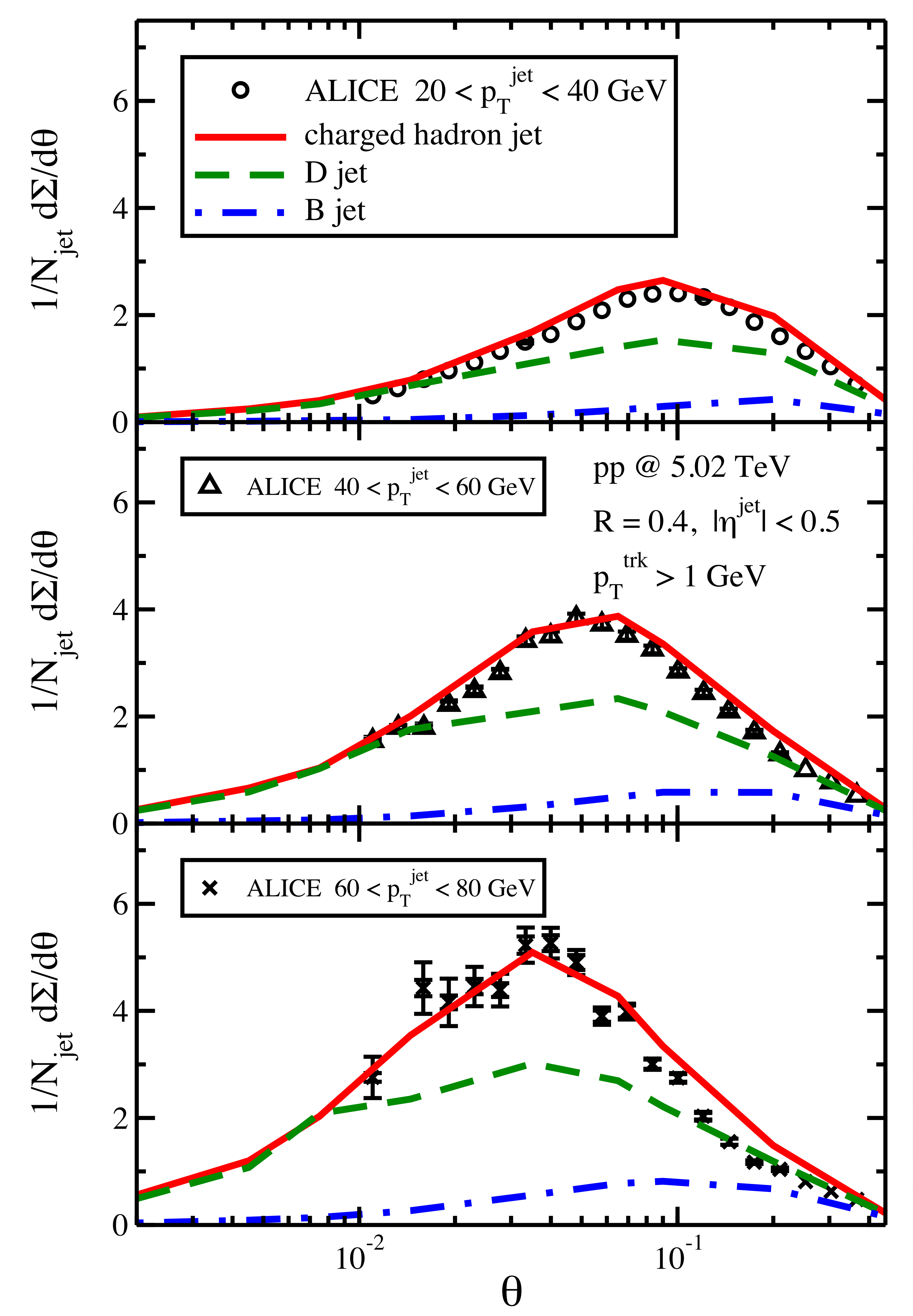

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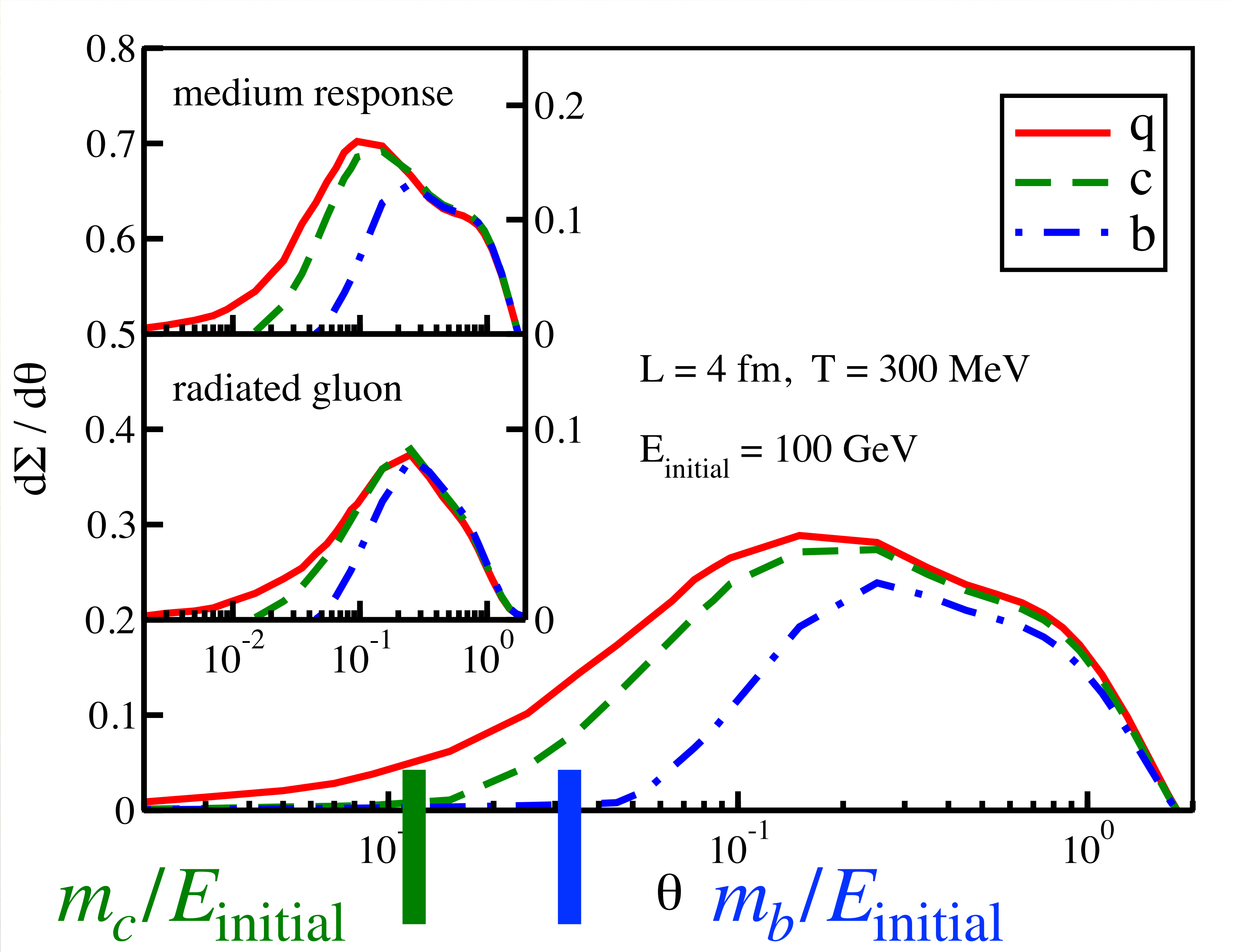
- Jet energy dependence
  - Higher $p_T \rightarrow \Sigma$ peaks at smaller θ

$p_T\theta_{peak}$ ~ transition scale between pert. and non-pert.

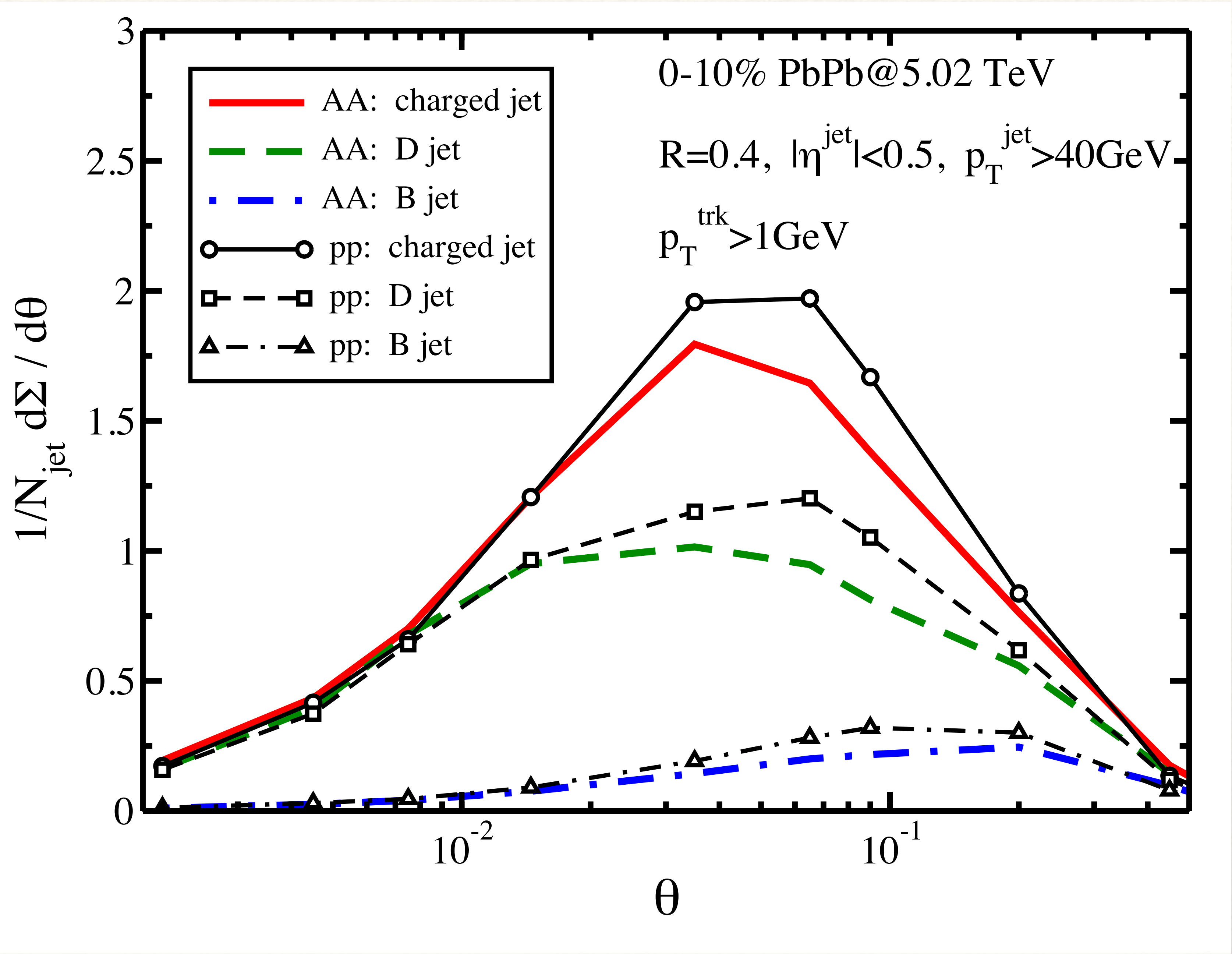
EEC of partons developed from a single quark

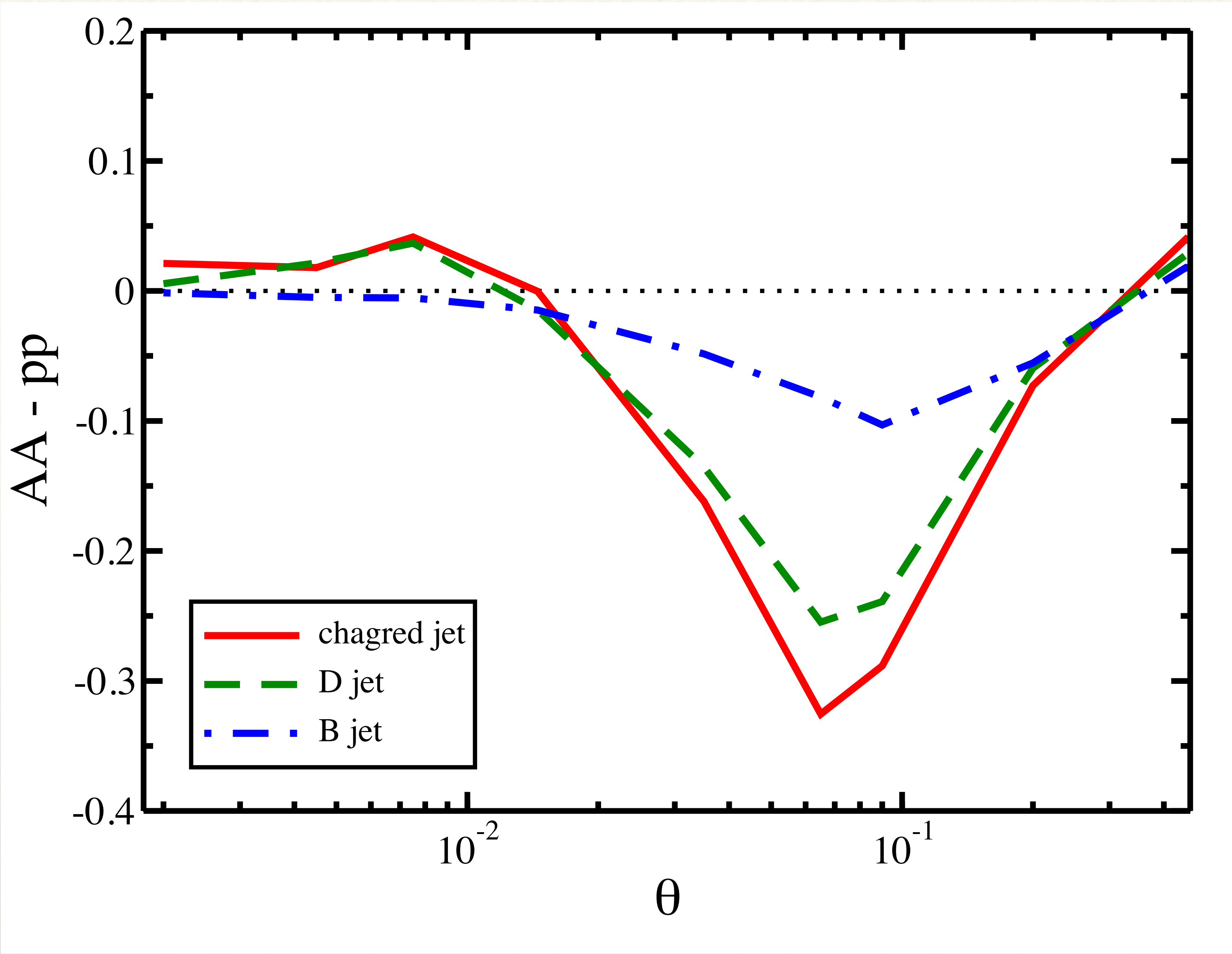


Xing, SC, Qin, Wang, arXiv:2409.12843

- Single quark → LBT + static medium → EEC of daughter partons
- Flavor (mass) hierarchy of EEC:
  - Magnitude: charged > *D* > *B*-jet; peak position: charged < *D* < *B*-jet (similar to vacuum jets)
  - Clear strong suppression of Σ below $\theta_0 \sim m_Q/E_{\mathrm{initial}}$
- Contributions form medium response and gluon emission show similar hierarchies

Light *vs.* heavy flavor jet EEC in central PbPb collisions

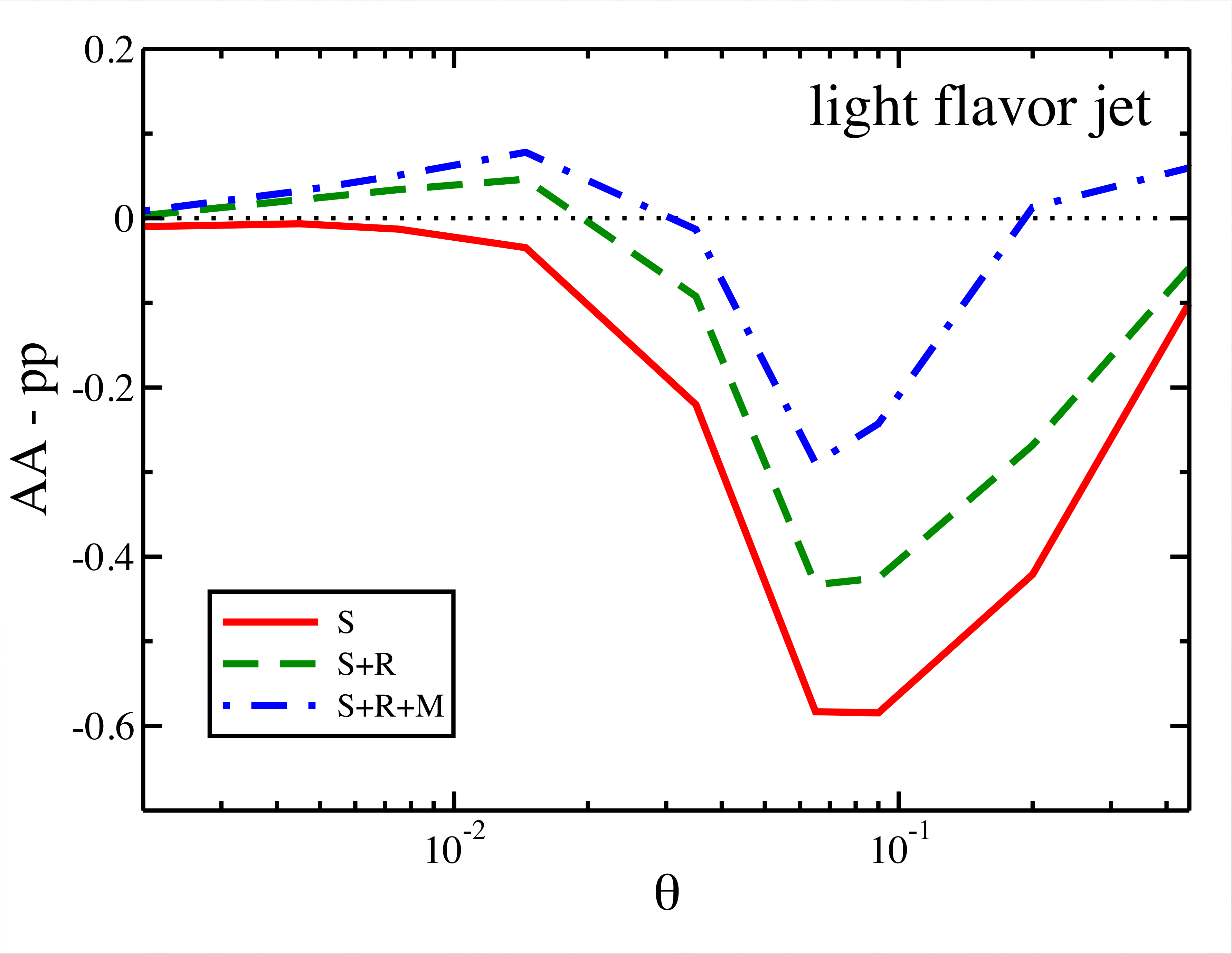




Nuclear modification (AA - *pp*) — Pythia + LBT in hydro

- General features: suppression at intermediate θ, enhancement at small θ (except for *B*-jet) and large θ
- Flavor hierarchy: weaker nuclear modification (both suppression and enhancement) for jets tagged with heavier mesons

Different contributions to medium modification on EEC



S: shower partons inherited from Pythia

S+R: add medium-induced gluons

S+R+M: further add medium response

- Jet energy loss causes suppression over the entire θ region
- Medium-induced gluon emission enhances EEC at small θ
- Medium response enhances EEC at large θ

Probing the EoS of QGP using heavy quarks

[F.-L. Liu, X.-Y. Wu, SC, G-Y. Qin, X.-N. Wang, Phys. Lett. B 848 (2024) 138355]

Transport

$$p_a \cdot \partial f_a(x_a, p_a) = E_a(\mathscr{C}_a^{\mathrm{el}} + \mathscr{C}_a^{\mathrm{inel}})$$

Strong coupling strength

$$g(E, T)$$

Thermal mass of partons

$$m_g^2 = \frac{1}{6} g^2 \left[(N_c + \frac{1}{2} n_f) T^2 + \frac{N_c}{2\pi^2} \Sigma_q \mu_q^2 \right]$$

$$m_{u,d}^2 = \frac{N_c^2 - 1}{8N_c} g^2 \left[T^2 + \frac{\mu_{u,d}^2}{\pi^2} \right]$$

$$m_s^2 - m_{0s}^2 = \frac{N_c^2 - 1}{8N_c} g^2 \left[T^2 + \frac{\mu_s^2}{\pi^2} \right]$$

Equation of state

$$P_{qp}(m_u, m_d, ..., T) = \Sigma_{i=u,d,s,g} d_i \int \frac{d^3p}{(2\pi)^3} \frac{|\vec{p}^2|}{3E_i(p)} f_i(p) - B(T)$$
$$= \Sigma_i P_{kin}^i(m_i, T) - B(T)$$

$$\epsilon = T dP(T)/dT - P(T), \qquad s = (\epsilon + P)/T$$

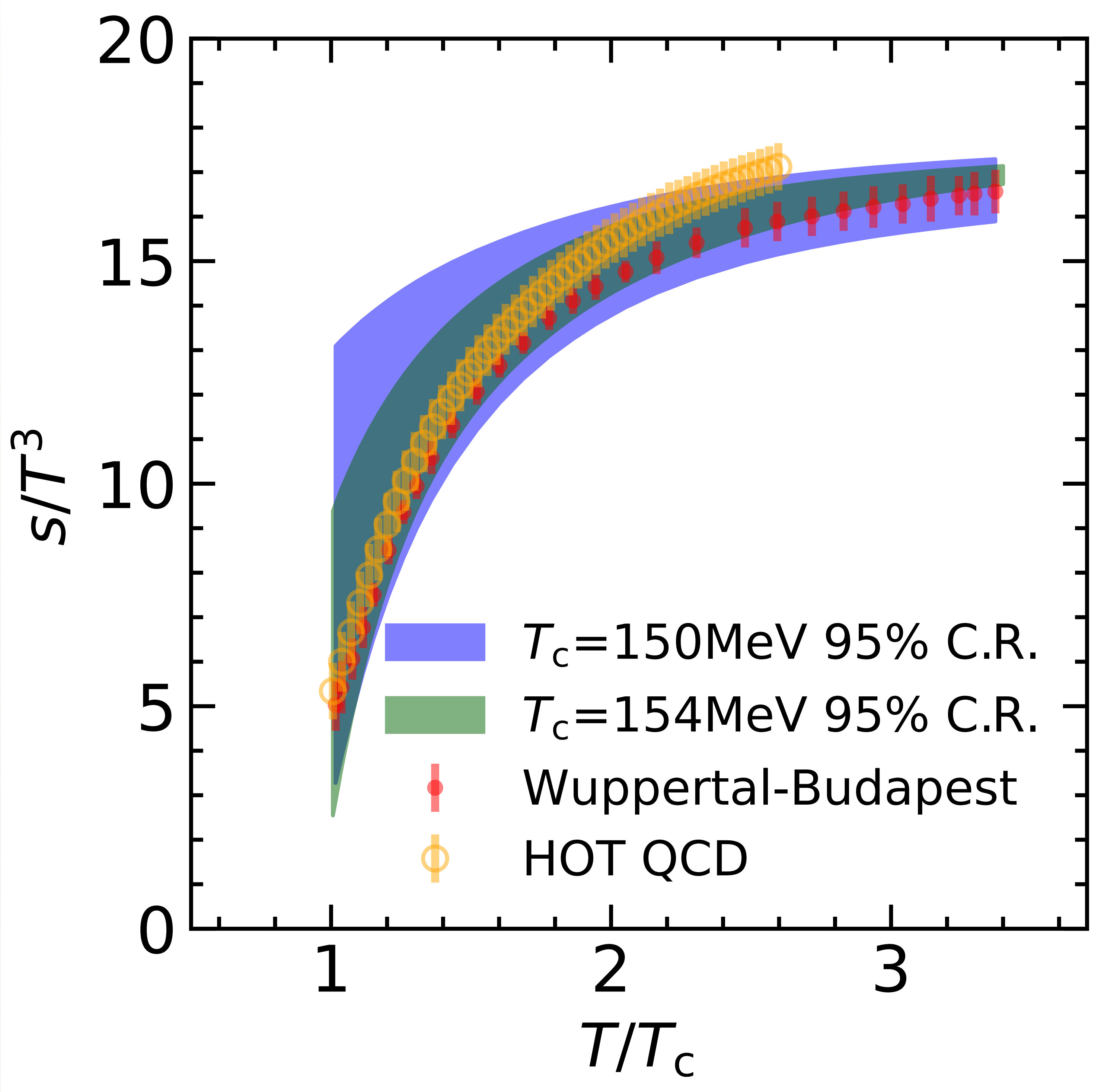
Strategy:

Fit g from comparing transport model to data

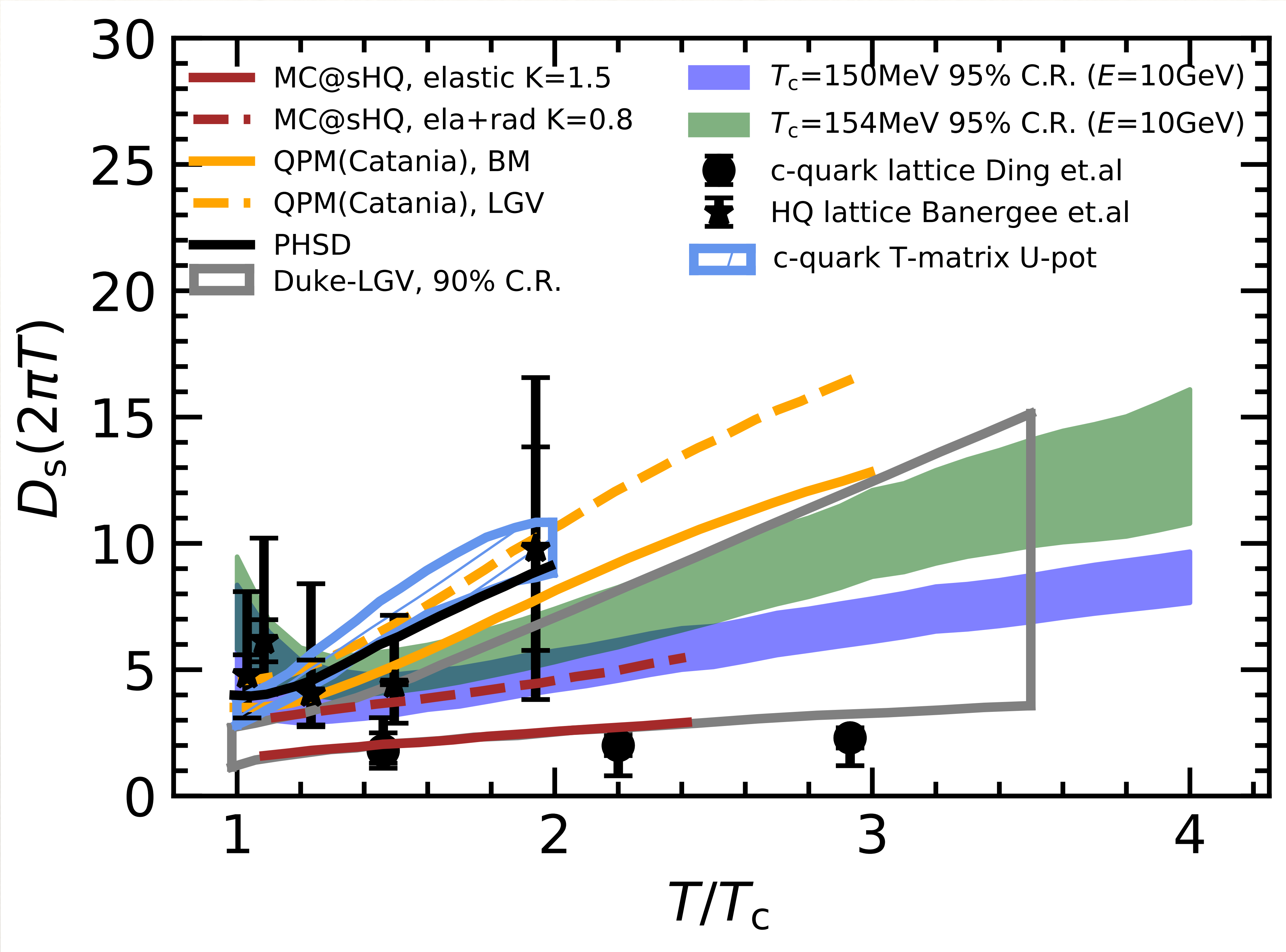
Calculate EoS from g

EoS of QGP and diffusion coefficient of heavy quarks

Equation of state of the QGP



Diffusion coefficient of heavy quarks



- Agreement with the lattice data
- Simultaneous constraint on QGP properties and transport properties of hard probes

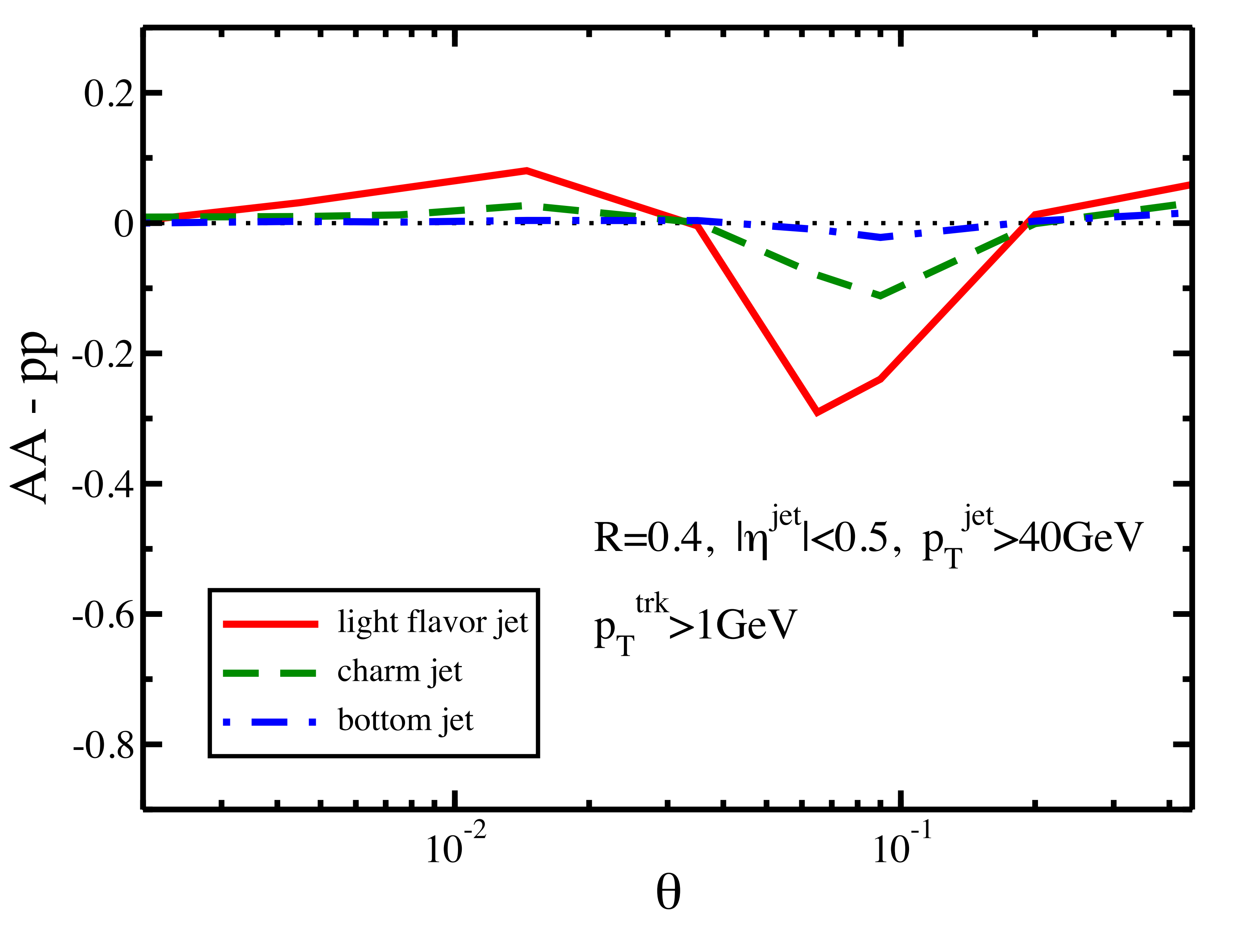
Summary

- Developed a transport model for studying both heavy flavor hadrons and jets
- Flavor hierarchy of parton energy loss is encoded in the hadron R_{AA}, though not explicit due to the interplay between energy loss and NLO contributions
- The jet EEC is an excellent observable to study the dead cone effect on parton splitting (magnitude and peak position of EEC) in both *pp* and AA collisions
- Heavy flavor observables can be used to constrain the QGP properties (EoS)

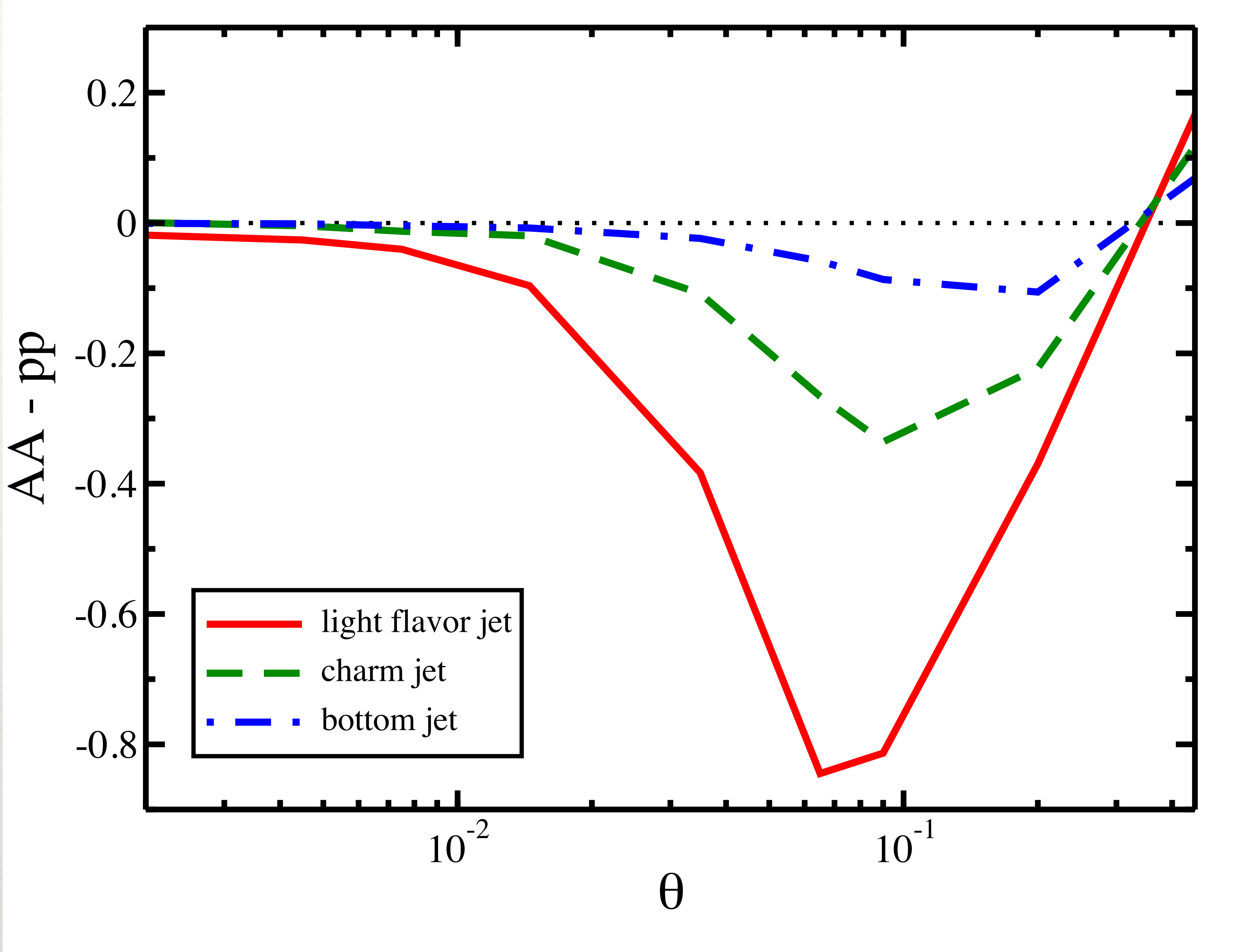
Thank you!

Effects of trigger bias on the jet EEC

p_T trigger in both *pp* and AA



p_T trigger only in *pp* (no trigger bias in AA)



- AA jets with trigger bias originate from *pp* jets with higher p_T and initial virtuality scale
  - → Stronger but narrower vacuum splittings
  - → Enhances EEC at small θ, reduces the suppression/enhancement at intermediate/large θ
- Can be tested using γ-jets

Parametrization and Bayesian analysis

Strong coupling strength

Interaction between thermal partons (thermal scale):

$$g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\frac{(aT/T_c + b)^2}{1+ce^{-d(T/T_c)^2}}\right]}$$

Interaction with hard partons (parton energy scale):

$$g^2(E) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[(AE/T_c + B)^2\right]}$$

Parameters: $\theta = (a, b, c, d, A, B)$

Bayes Theorem

$$P(\boldsymbol{\theta}|\text{data}) \propto P(\text{data}|\boldsymbol{\theta})P(\boldsymbol{\theta})$$

posterior distribution

prior distribution

model-to-data comparison

$$P(\text{data}|\boldsymbol{\theta}) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{[y_i(\boldsymbol{\theta}) - y_i^{\text{exp}}]^2}{2\sigma_i^2}}$$

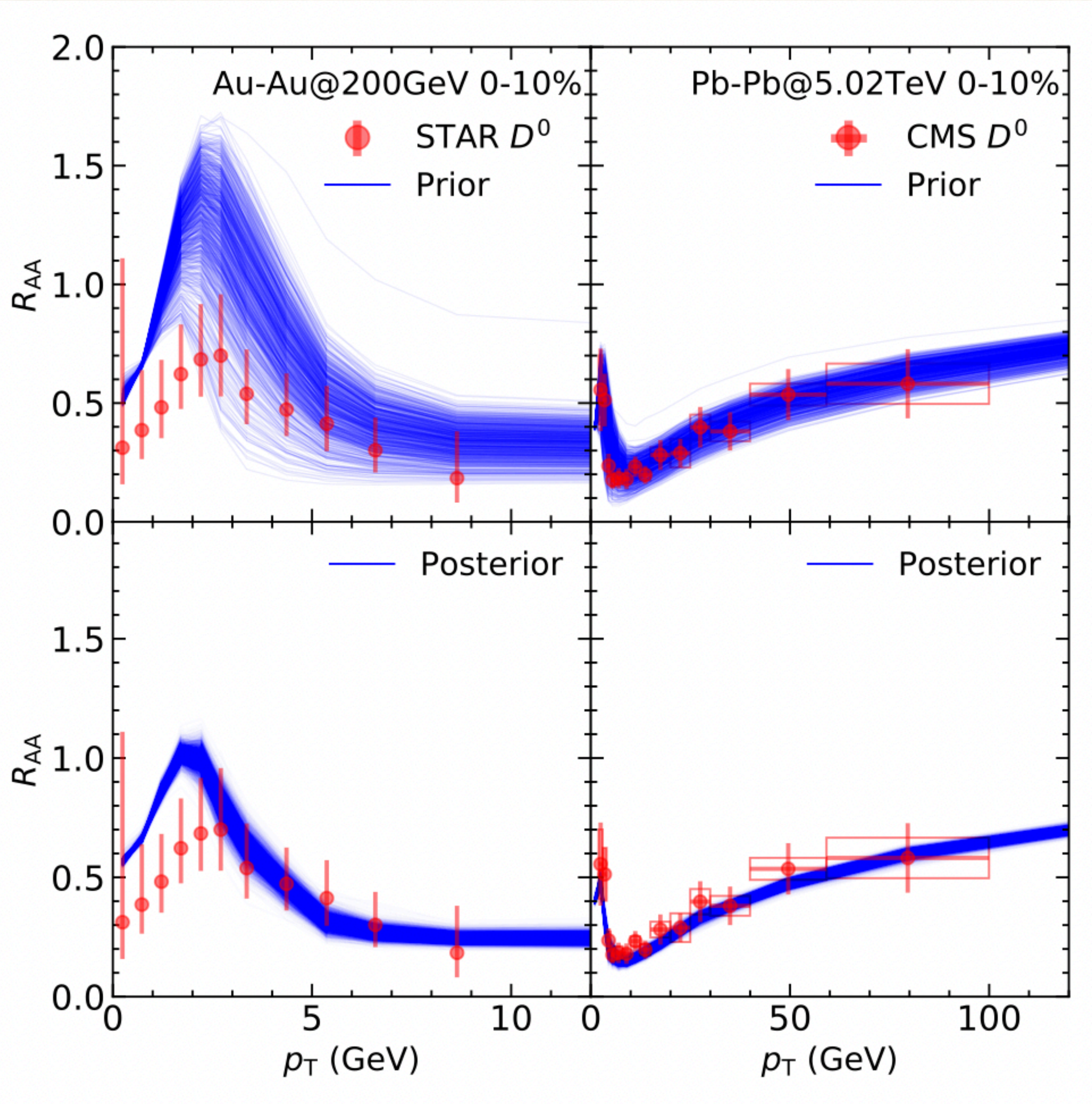
Model calibration and parameter extraction

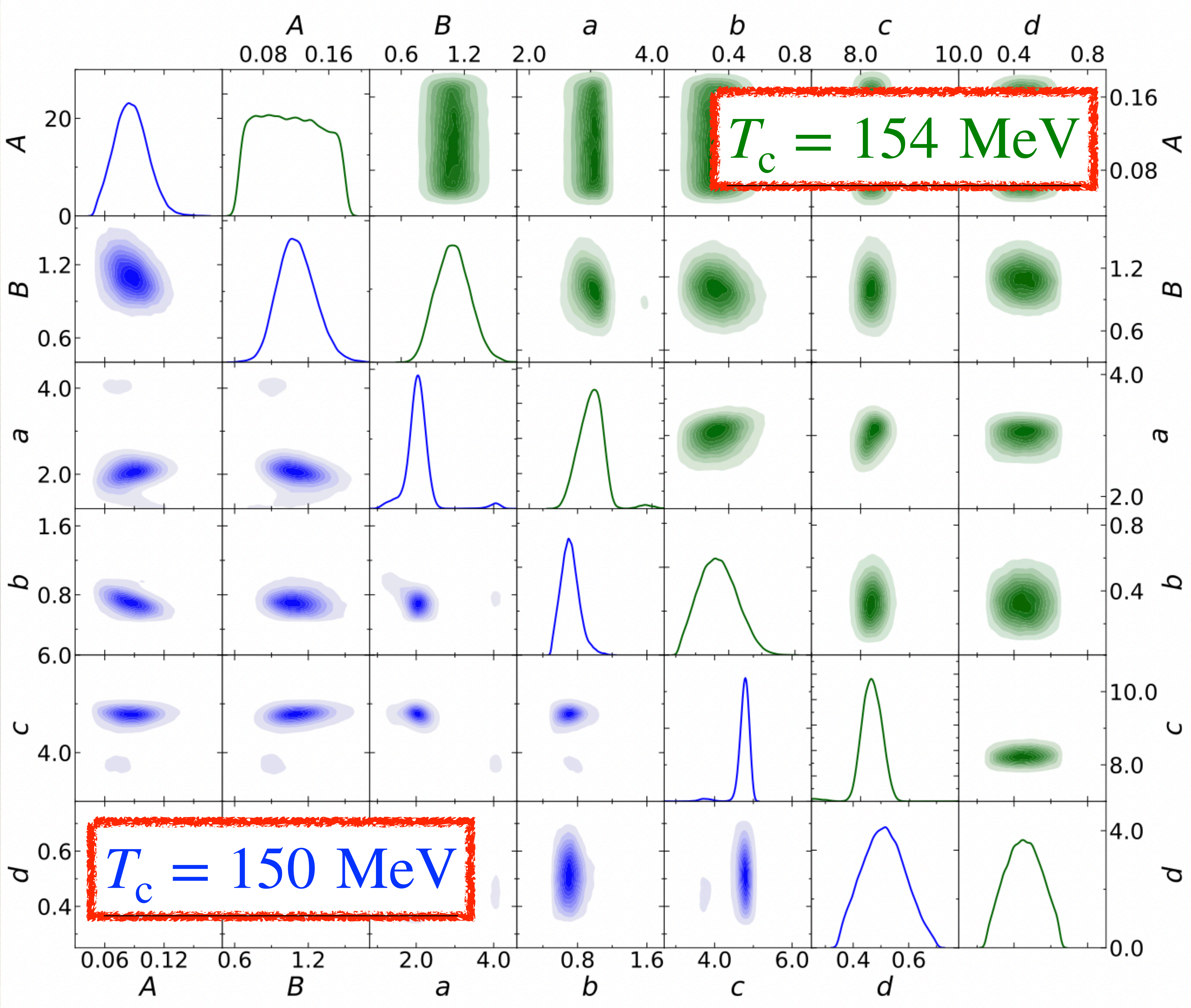
Calibration against observables

Extraction of model parameters for $g(E,T)$

prior

posterior





(Two examples from many observables)